Additive manufacturing for the spare part management of classic cars

by

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Declaration

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Abstract

The maintenance of older vehicles can be challenging since the supply of spare parts by the original equipment manufacturer is not guaranteed throughout the lifespan of a vehicle. Thus, there is a need to improve the current spare part supply chain for the automotive industry specifically for outdated products like classic cars. Within the automotive industry additive manufacturing (AM) technology is already being implemented in the production cycle of new cars. The need to improve the supply of spare parts for classic cars and the increased use of the AM technology raised the question whether additive manufacturing can have an impact on the spare part management of classic cars. In order to answer this question, this research study started with the review of literature.

Three critical scoping literature reviews were undertaken to analyse the current performance of the spare part management of classic cars and to identify spare part attributes for the ranking of spare parts according to their potential for additive manufacturing. To fully understand the spare part management of classic cars, a first literature study on the classic car market was conducted. A second literature review on spare part management within the automotive industry utilized a performance measurement model to measure the impact of adopting additive manufacturing. Based on this, the applicability of additive manufacturing was the subject of the third literature review. Results show that a potential for additive manufacturing exists, and it can be measured with spare part attributes. Based on these results, it was decided to follow an exploratory research design approach.

A survey was conducted with classic car owners to identify sourcing problems of spare parts and to assess their willingness to adopt additive manufacturing. The data from the survey was analysed using a ranking methodology from science which was modified toward the application of additive manufacturing on the spare part management of classic cars. The outcome of the ranking highlighted that small parts (e.g. switches) and batches are best suitable for additive manufacturing. A Delphi survey with subject-matter experts validated the ranking method. A case study was carried out in which a speedometer gear was reverse-engineered, additive manufactured and tested under realistic conditions. The case study highlighted that additive manufacturing is feasible to produce spare parts on demand and on a decentralized implementation strategy.

Overall, this research has shown that additive manufacturing has a high potential to impact the spare part management of classic cars. The research result showed that unsatisfied customer demand is recognised. Additive manufacturing is a technologically feasible solution to produce many spare parts and has the high potential to increase the supply chain performance of classic car spare parts.

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Opsomming

Die instandhouding van ouer voertuie kan uitdagend wees aangesien die verskaffing van onderdele deur die oorspronklike toerusting vervaardiger nie deur die lewensduur van 'n voertuig gewaarborg word nie. Daar is dus 'n behoefte om die huidige onderdele-voorsienings ketting vir die motorbedryf te verbeter, spesifiek vir verouderde produkte soos klassieke motors. Binne die motorbedryf word additive manufacturing (AM) tegnologie reeds in die produksie siklus van nuwe motors geïmplementeer. Die behoefte om die verskaffing van onderdele vir klassieke motors te verbeter en die verhoogde gebruik van die AM-tegnologie het die vraag laat ontstaan of bykomende vervaardiging 'n impak op die onderdelebestuur van klassieke motors kan hê.

Drie kritiese literatuur oorsigte is onderneem om die huidige prestasie van die onderdele bestuur van klassieke motors te karteer. Eerstens is 'n literatuuroorsig oor die klassieke motormark gedoen. Die volgende twee literatuur oorsigte oor onderdele bestuur binne die motorbedryf en bykomende vervaardiging vir motoronderdele het 'n prestasie metings model gebruik om die impak van die aanvaarding van bykomende vervaardiging te meet. Resultate toon dat 'n potensiaal vir bykomende vervaardiging bestaan. Op grond van hierdie resultate is daar besluit om 'n verkennende navorsings ontwerp benadering te volg.

’n Opname is met eienaars van klassieke motors gedoen om die verkrygings probleme van onderdele te identifiseer en om hul gewilligheid om bykomende vervaardiging aan te neem, te bepaal. Die data van die opname is ontleed deur gebruik te maak van 'n rangorde metodologie uit die wetenskap wat aangepas is na die toepassing van bykomende vervaardiging op die onder delebestuur van klassieke motors. Die uitkoms van die rangorde het beklemtoon dat klein onderdele (bv. skakelaars) en groepe die beste geskik is vir bykomende vervaardiging. 'n Delphi-opname met vakkundiges het die rangorde metode bekragtig. ’n Gevallestudie is uitgevoer waarin ’n spoed-meterrat omgekeerd ontwerp is, ´n bymiddel vervaardig en onder realistiese toestand getoets is. Die gevallestudie het beklemtoon dat bykomende vervaardiging haalbaar is om onderdele op aanvraag en volgens 'n gedesentraliseerde implementering strategie te vervaardig.

Oor die algemeen het hierdie navorsing getoon dat bykomende vervaardiging 'n hoë potensiaal het om die onderdele bestuur van klassieke motors te beïnvloed. Die navorsings resultaat het getoon dat die onbevredigde vraag erken word. Bykomende vervaardiging is 'n tegnologiese haalbare oplossing om baie onderdele te vervaardig en het die hoë potensiaal om die voorsienings ketting prestasie van klassieke motoronderdele te verhoog.

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Chapter 1
Introduction

1.1 Background and motivation for study

Automobile manufacturers are obliged to guarantee the supply of spare parts for new vehicles for up to ten years after the series production has ended. Beyond this period, it is the manufacturer's choice which spare parts they decide to continue supplying (Klug, 2010). Various factors influence their decision with the main factors being manufacturing cost and demand. The rarity of many classic cars results in a low demand for spare parts. The low demand for spare parts results, in turn, in limited spare part supply since many cases can be considered as uneconomic. Thus, there is a need to improve the current spare part management of classic cars.

Within the automotive industry additive manufacturing technology is already being implemented in the production cycle of new cars. The technology enables the production of low volume or customised products and has started to attract interest in the generation of spare parts for some cars (Montero et al., 2019). The benefits of using additive manufacturing for the production of spare parts are "low prices for essential parts, a shorter waiting-time for the delivery of critical and specialist parts and less dependence upon manufacturers to support ageing products" (Reeves and Mendis, 2015, p. 5). One advantage of 3D printing is the relatively cheaper production of individual items compared to batch production, which can also be used in the classic car industry. Thus far, spare parts for classic cars have been reproduced based on necessity and demand using conventional manufacturing processes. Technical components, such as components for brakes and chassis, are available for almost all vehicles. However, the range does not extend to products in the car interior or decorative elements on the car body, since the quantities required for conventional production are not in sufficient demand. With innovative technologies such as 3D printing, the production of spare parts in small quantities might be a promising opportunity for the spare part management of classic cars (Crepon, 2017).

1.2 Problem statement

The classic car market is a fast-growing market. The number of cars produced per year by the 50 largest manufacturers increased by 65% in 20 years (1996 to 2016). This increase will also be

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reflected in the number of classic cars, once these cars turn 20 years old. The car manufacturer and supplier, known as original equipment manufacturers (OEM), however, guarantees the supply of spare parts for only 10 to 15 years after the end of series production (Boissie *et al.*, 2018). High costs of carrying inventory lead most automotive part distributors and retailers to stock only commonly sold parts after the guaranteed supply period. Therefore, several spare parts for classic cars are no longer available on the aftermarket. Post-production of spare parts in low volume with conventional production methods is uneconomical as the overall demand is low in many cases (Inderfurth and Kleber, 2013). Additive manufacturing may therefore provide a potential low-volume cost-effective alternative to produce these spare parts.

1.3 Research aim and objectives

The aim of this research is to investigate if the spare part supply of classic cars can be improved with additive manufacturing. This investigation is characterized by analysing if spares of existing parts can be produced effectively with additive manufacturing. This aim was accomplished by addressing three research objectives:

(1) Analyse the current spare part management of classic cars to identify improvement potentials for the use of additive manufacturing

(2) Investigate the improvement potentials and explore the feasibility of producing spare parts using additive manufacturing

(3) Design an implementation approach for the use additive manufacturing to produce classic car spare parts and estimate the potential impact

1.4 Contributions

Stakeholders in the spare part supply chain of classic cars might be investigating the potential impact of additive manufacturing on their industry to stay competitive with competitors. However, a holistic approach for the measurement of the potential of additive manufacturing for the production of classic car spare parts is not developed yet. This research closed the relevant gaps in literature and helps companies to analyse the potential of additive manufacturing by utilizing this research methodology. The potential analysis might lead the company to adopt additive manufacturing, which is presumed to increase the spare part availability and strengthen the supply chain performance of classic car spare

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parts (Delic and Eyers, 2020; Knofius, van der Heijden and Zijm, 2016). This positive effect on the spare part management can increase the satisfaction of customer demand and helps to preserve automotive history.

1.5 Scope and delimitations

The aim of this research was to estimate the impact of additive manufacturing on the spare part management of classic cars. The impact was measured by comparing the actual state of spare part management of classic cars with a developed future state utilizing additive manufacturing. To get a holistic overview of the current spare part management of classic cars, a large scope for the literature review was chosen to collect all relevant information. It turned out that three literature reviews on different topics had to be conducted to address all relevant topics.

In a second phase, the future state of the spare part management utilizing additive manufacturing had to be developed. By conducting an additional literature review on existing methods which analyse the impact of additive manufacturing, one method was identified which suited the research aim of this research. To extend the scope, this methodology from literature was extended by a single case study. However, the conduct of the methodology was also limited by the unavailability of a company's data and information.

Although a multiple case study would have strengthened the research outcome only a single case study was carried out to extend the method from literature. Limited time did not allow the manufacture and testing of multiple parts. Furthermore, a comparison of the conventional way of manufacturing spare parts with the future state using additive manufacturing in a cost analysis could have strengthened the conclusion on the impact of additive manufacturing. However, in this case study the focus was set on analysing the manufacturing process and investigating the technological feasibility of additive manufacturing by manufacturing a working prototype. Therefore, relevant information regarding the costs of meeting, for example, technological or legal requirements were not available. Without this information a working prototype cannot be compared with a market ready spare part.

In addition to the aforementioned limitations which are mostly concerning the resource time, it has to be mentioned that this research was limited by the Covid-19 pandemic. In various phases of this research the laboratory for additive manufacturing was operating under restricted conditions. Since

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the restrictions were not predictable, it was decided to conduct all possible research outside the University of Stellenbosch. This approach brought along that some methods had to be performed in a “Do-it-yourself” style. For example, the professional microscope for the analysis of the wear in the case study was replaced by a smartphone and a lens. Nevertheless, this approach was identified to be feasible for the scope of this research.

1.6 **Document roadmap**

The introduction to this research study in Chapter 1 provided the background and motivation for undertaking the research, followed by the problem statement which defined the need to consider additive manufacturing in the supply chain of classic cars. A set of research objectives was described to show how the project aim was achieved. Next, the contributions were highlighted and the research methodology was critically discussed by its scope and limitations.

In Chapter 2, the scoping literature reviews set a base of knowledge on the spare part management of classic cars. Three scoping literature reviews had to be conducted since no literature was available on this specific topic. The first literature review gave an overview of the classic car market. From there, the literature addressing the current spare part management of automotive spare parts was analysed in order to understand various spare part management approaches. Subsequently, the additive manufacturing process for the production of automotive parts was investigated.

In Chapter 3 the choice for an exploratory research design was explained. In the scope of the exploratory research design another literature review was conducted to identify feasible research methodologies for this research study. The methodology chosen was modified to suit the scope and limitations of this research. During this chapter, the customisations of the methodology and the additional methods chosen for this research were introduced.

The conduct of the customised methodology is split into two chapters. Chapter 4 describes all methods regarding the ranking of spare parts. This includes the process of conducting the market survey. The outcome of the market survey was a database of spare parts which was further analysed with the ranking method. The outcome of the ranking method was validated in a Delphi Survey with subject-matter-experts.

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In Chapter 5 the process and outcome of the single case study was explained. The process of the case study consisted of the manufacturing and testing of the selected spare part. The outcome of the case study was characterised by the wear behaviour observed after performing the test.

Chapter 6 brought together the results of the surveys, ranking method, and case study by discussing a potential implementation approach of additive manufacturing. In addition, the information gathered throughout the methodology were applied on the supply chain performance measurement model to measure the potential impact of additive manufacturing. In Chapter 7, the research study was concluded and contributions towards practice were highlighted.

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Chapter 2

Literature Study

2.1 Introduction

The literature study gave insight into the existing knowledge and concepts of various thematic areas that are essential to answer the research objectives. There is currently no published literature available regarding additive manufacturing for spare parts of classic cars. This chapter is, therefore, arranged into sub-topics to sequentially analyse the three relevant topics. In order to fully understand the spare part management of classic cars, a literature study regarding the classic car market was conducted to understand the characteristics of classic car market and the role of the spare part management. This is followed by a literature review on the spare part management in the automotive industry to understand the role of classic cars. Thirdly, a literature review on the use of additive manufacturing for the production of spare parts in the automotive industry was developed. Combining the information of all three literature reviews, the impact of additive manufacturing on the spare part management of spare parts for classic cars was assessed based on previously published research. Figure 2.1 maps the three literature review topics with the relevant content of each review. Each literature topic is illustrated by a model to provide structure for the analysis of literature and the summary of the results.

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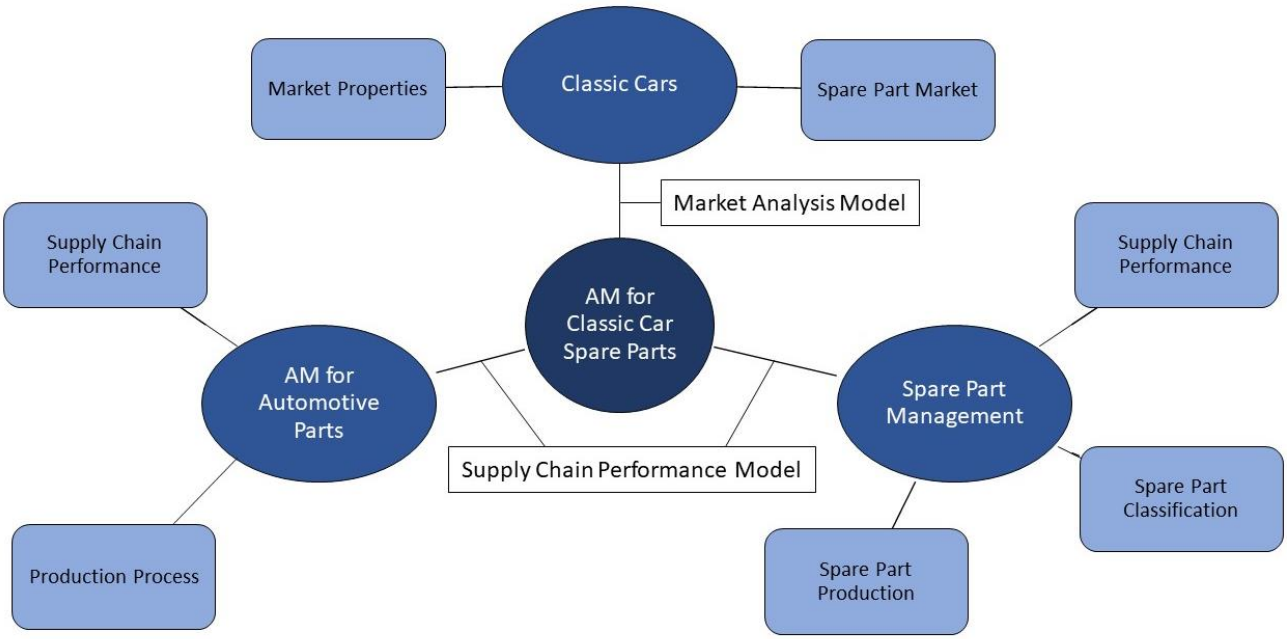

Figure 2.1: Issues regarding the use of additive manufacturing for the spare part management of spare parts for classic cars

2.2 Literature review methodology

Literature dealing with the influence of additive manufacturing on the spare part management of spare parts for classic cars is not existing yet. Therefore, the scope of considered literature needs to be broader. A suitable literature review method for analysing and mapping literature on a specific topic is the scoping literature review. Scoping literature reviews are used, inter alia, "to examine how research is conducted on a certain topic" or "field and identify key concepts" (Munn *et al.*, 2018). Peters *et al.* (2015) provides guidance for conducting a systematic scoping review. This traditional framework of systematic scoping reviews requires two researchers. Since this research is limited to only one researcher, the modified systematic scoping framework of Davison (2019) is utilized for this literature review. Her simplified framework, in comparison to the traditional framework of Peters *et al.* (2015), consists of a 6 step process, which is shown in Figure 2.2. Starting off with defining the research question for the literature review, relevant articles are searched, and the data of the literature are charted. The information from literature is then summarised and concluded in a consultation exercise.

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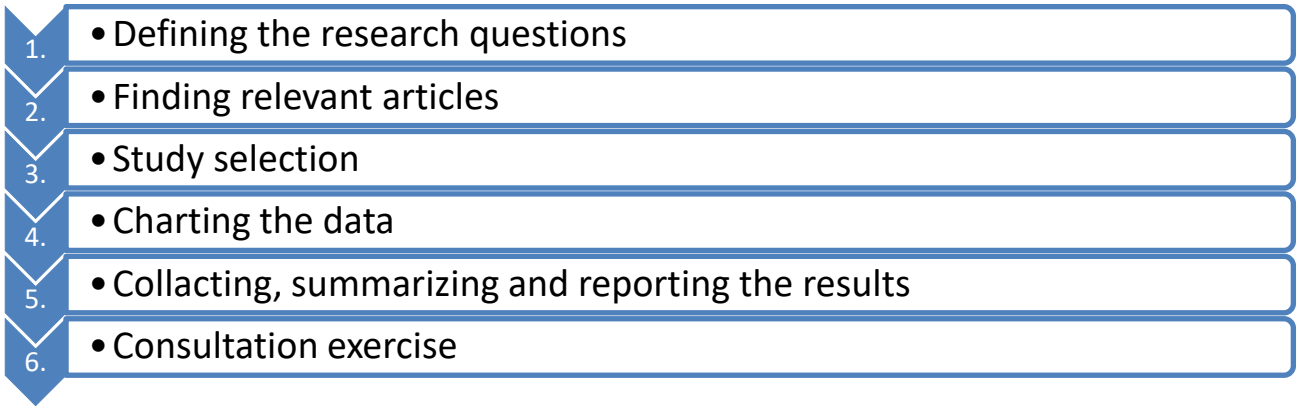

Figure 2.2: Systematic scoping literature review in 6 steps, adapted from Davison (2019)

2.3 Classic car market

2.3.1 Introduction

The literature review on the classic car market utilized two different frameworks (Figure 2.3) to analyse and chart published literature. Framework 1 was implemented to structure the search for literature and data according to a market research model. The market research model used in this project was "Porter's Five Forces Model", explained in Chapter 2.3.2. Porter's model was provided with information from Framework 2. Framework 2 used the scoping literature review from Davison (2019) to access secondary data and literature on the classic car market. The method of a scoping review was described in "Chapter 2.2".

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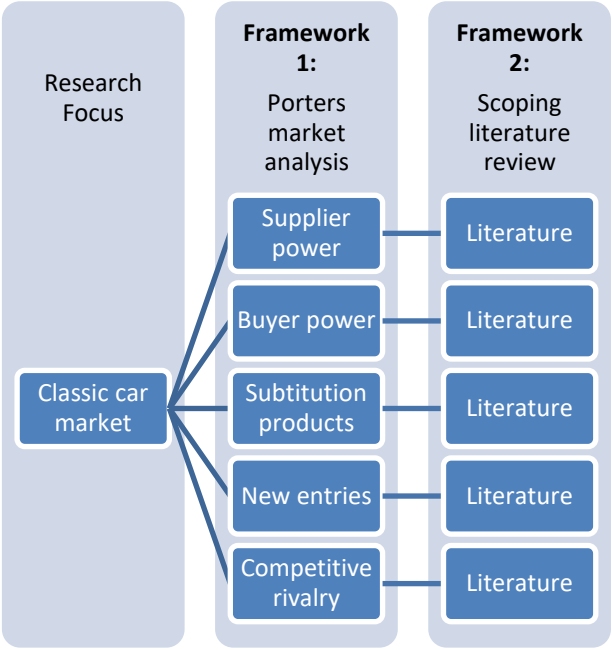

Figure 2.3: Structure of the literature review of the classic car market

2.3.2 Market research model

The model used for the research on the classic car market is the "Five-Forces Model" by Michael Porter, which is one of the most applied strategic frameworks for market analyses (Pringle and Huisman, 2011). This industry structure model offers an analysis grid with which the structure of an industry and the competitive position of companies can be systematically examined. This can help a company to determine whether enabling long-term profitable developments in a market is feasible (Hartung and Rohatsch, 2018). While some industries' total competitive forces are very strong with high ability to push profits of all competitors to a relatively low level, other industries' average profitability is high due to lower market forces (Müller, 2006).

The five market forces reviewed in Porter's framework are shown in Figure 2.4 and are described in the following:

- Rivalry among existing competitors: Rivalry among existing competitors takes many familiar forms, including price discounting, new product introductions, advertising campaigns, and service improvements. High rivalry limits the profitability of an industry (Porter, 2008).
- Bargaining power of suppliers: The negotiating power of suppliers determines how much they can assert their interests in a business relationship with their customers. A high level of supply bargaining power will generally result in either higher prices or the ability to deliver less quality at the same price (Swaan Arons and Waalewijn, 1999).

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- Bargaining power of buyers: As with suppliers, the negotiating power of customers determines how much customers can assert their interests in a business relationship with the supplier. A high level of bargaining power of customers will generally result in either being able to demand lower prices or obtain better quality at the same price (Swaan Arons and Waalewijn, 1999).
- Threat of substitute products: A substitute performs the same or a similar function as an industry's product by a different means. A substitute is also defined as going without the product, to purchase a used product, or to do it yourself (Porter, 2008).
- Threat of new entrants: New entrants to an industry bring new capacity and a desire to gain market share that puts pressure on prices and quality to compete (Porter, 2008)

Figure 2.4: Porters Five Forces market analysis model, adapted from Porter (2008)

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2.3.3 Literature review – Classic car market

The secondary market research used the framework of the scoping review explained in Chapter 2.2. The aim of this first scoping literature review is to find relevant articles considering general market characteristics. In the following, the six steps of the scoping review were conducted.

Step1: Identifying the research questions

The success of using additive manufacturing to produce spare parts for classic cars could have been measured by the competitiveness of additive manufactured spare parts on the market. Due to the limited resources of this research study, a measure of competitiveness on the market was unfeasible. To analyse and predict the competitiveness of additive manufacturing for spare parts, the market proportions were defined. The following research questions for this literature review were developed to collect information about the market proportions, influenced by the Porters Five Forces market model:

Reserch Question 1	How strong is the bargaining power of buyers in the classic car and spare part market?
Reserch Question 2	How strong is the bargaining power of suppliers in the classic car and spare part market?
Reserch Question 3	Are there substitute products for classic cars or substitues for their spare parts?
Reserch Question 4	Are there new entrants recognized in the classic car or spare part market?

Step 2: Identify relevant studies and statistics

The scoping literature review recommends the initial search to be as comprehensive as possible, from a wide range of sources (Arksey and O'Malley, 2005). Basic exclusion criteria based on the date of publication were not given to increase the number of articles. For the same reason, all sources written in English and German were considered. The final search strategy included e-databases SAGE, Science Direct and Springer Link. These Databases were accessed through the membership of “University of Stellenbosch” and “Hochschule München”. Entries from Google Scholar were accepted due to a limited number of scientific studies.

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Searching was executed using the following two search strings, one in English and one in German:

- “classic car” OR “vintage car” OR “aged car” AND “market” OR ”figures” OR “properties”;
- „Oldtimer” OR „klassisches Auto” And „Markt” OR „Zahlen“ OR „Eigenschaften“

To include Government Statistics which count the number of classic cars registered on the road, the official data bases from America, Germany, France, and Italy were accessed through Google search. Only the German government published statistics which included the relevant characteristic “Year of Production” of the vehicle. These Government statistics, in addition to the Google Scholar results, were added to the Google Database.

Step 3: Select studies and statistics

The PRISMA-ScR flow diagram was used as a template to illustrate the record selection process for the review (Figure 2.5). In the Identification phase 173 records were found in the four electronic databases. The title and abstracts of these records were screened in phase two. In this phase, 112 records were excluded because their content did not suit the research questions of this literature review. The resulting 61 records were assessed, in the third phase, in a full-text analysis to identify whether the content is contributing towards a base of knowledge, or whether the record has to be excluded. In the last phase, the remaining nine records were analysed for the inclusion in this scoping literature review.

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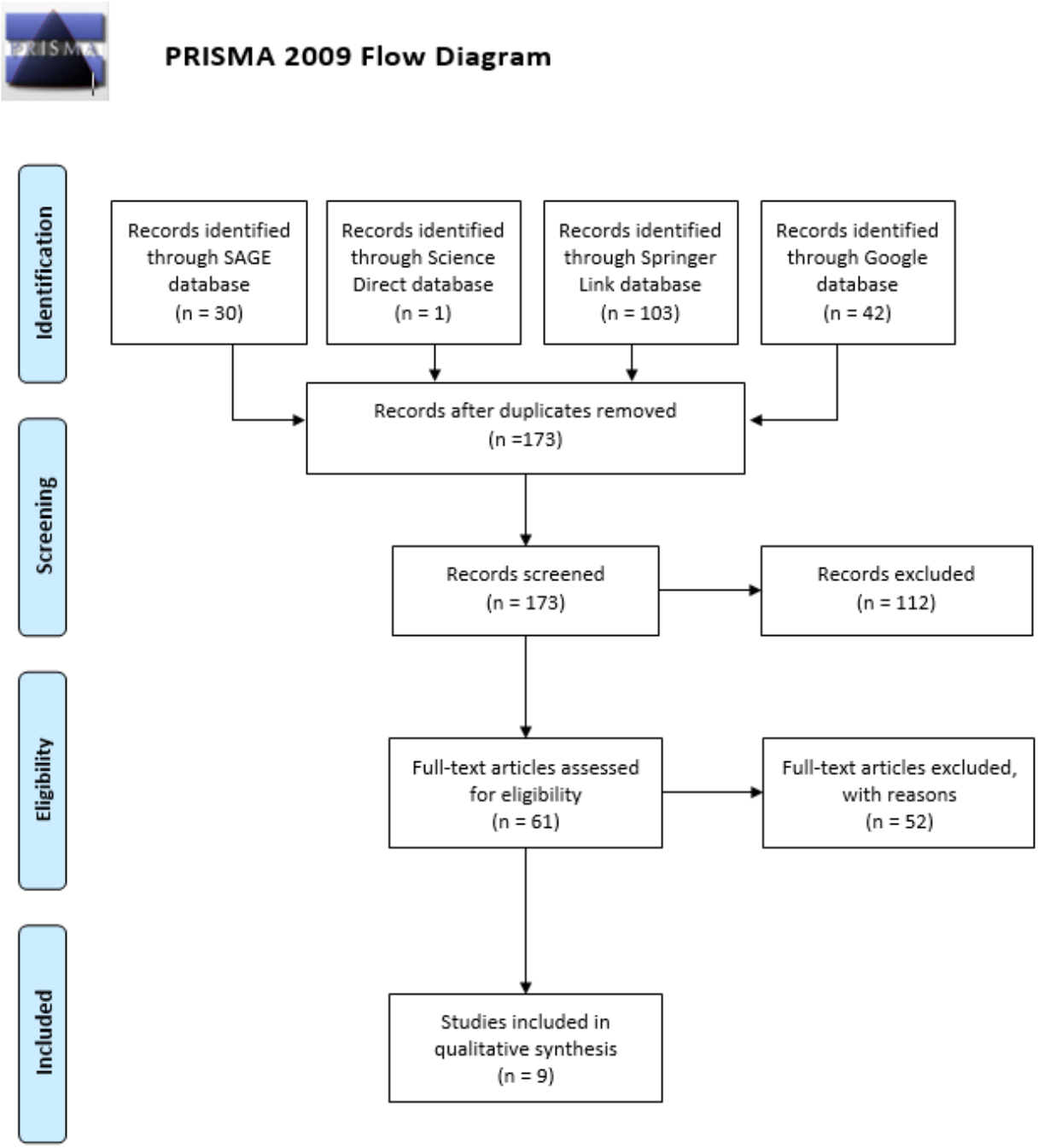

Figure 2.5: PRISMA-ScR Flow Diagram for the literature review of the classic car market, adapted from Rouse (2016)

Step 4: Chart the data

The included documents were categorized, as listed in Table 2.1, using the qualitative data analysis software "ATLAS.ti". Information and data identified as relevant were extracted out of all studies. In the following, a logical and descriptive summary of this information and data is presented to answer the research questions for this chapter (Peters *et al.*, 2015).

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Table 2.1: Categories for the analysis of literature

1. Record characteristics	• Title • Year of publication • Location of publication • Geographical focus • Publication type
2. Focus area of the records	• Classic car market figures • Classic car as investment • Classic cars for sustainability • Classic car market properties

All publications dealing with classic cars were considered without limitation to the year of publication. Figure 2.6 presents the records according to the year of publication. The figure indicates that most records found were published between the years 2017 to 2020. Concurrently, one record published in 1998 shows that classic cars also received interest decades ago.

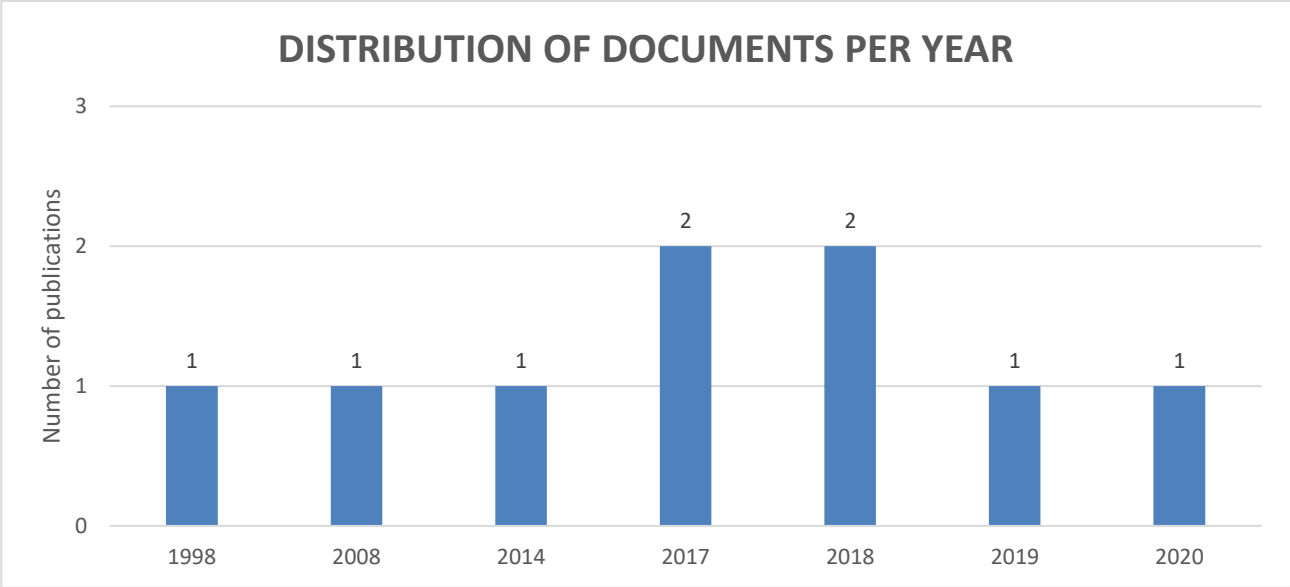

Figure 2.6: Distribution of documents per year for the literature review of the classic car market

The analysis of the type of publication indicated that most literature has been published in articles or papers (Figure 2.7). Only one book section, published by Springer, was accessible and included usable content. Two master theses that were published at the University de Louvain and accessed through Google Scholar, were added to the literature analysis. Four additional documents were found on Google Scholar. All entries from Google scholar fall into the category of "Grey-Literature" (Conn

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et al., 2003). Grey-Literature is defined as "unpublished studies, or studies that are published outside the widely available journals" (Conn *et al.*, 2003) . The use of Grey-Literature is risky because there is often little or no scientific representation of data (Soldani, Tamburri and van den Heuvel, 2018). To maximize the input data for this literature review, Grey-Literature is accepted in this literature review.

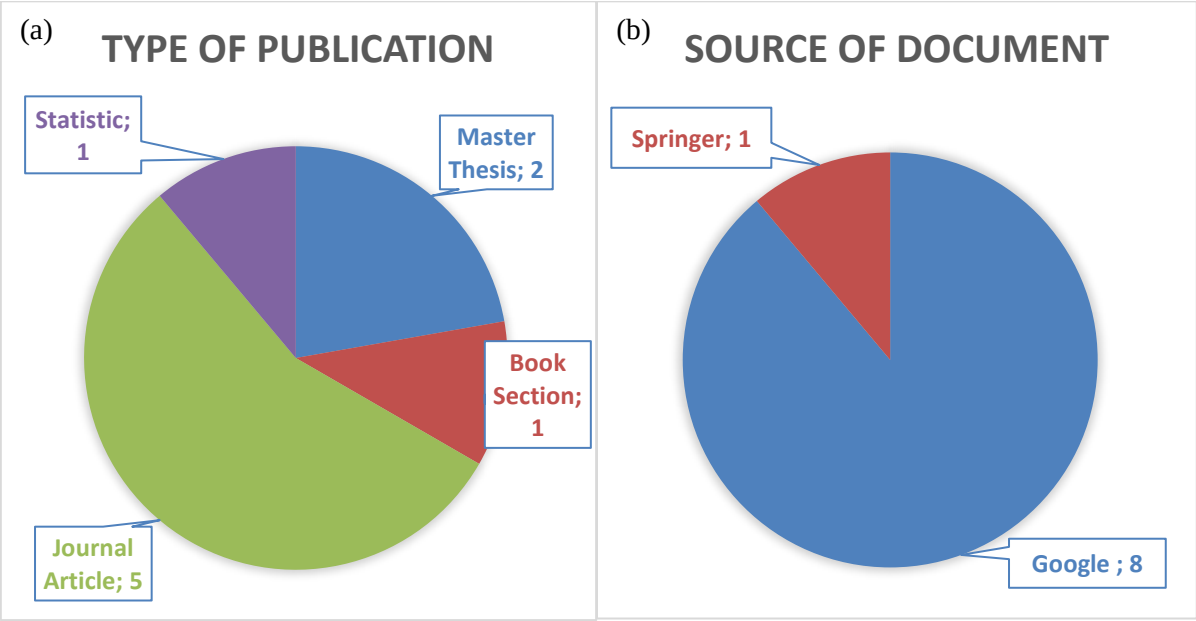

Figure 2.7(a) and (b): (a) Type of publication of the documents found for the literature of the classic car market; (b) Source of the documents found for the literature review of the classic car market

Considering the geographical location of published literature, Figure 2.8 states that 6 out of the 9 articles were published in Europe. One publication from America and one from Australia were considered in this scoping review. Although three documents were published in Germany, only one of them is written in German. The other seven documents are written in English.

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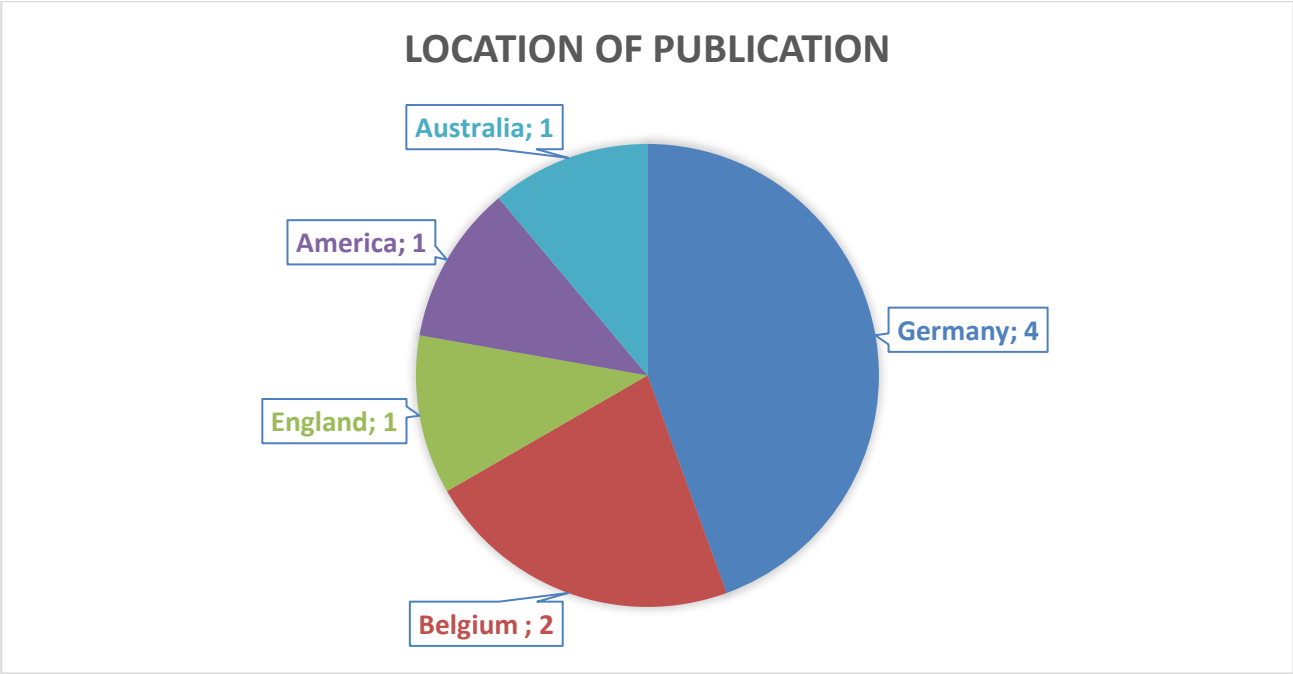

Figure 2.8: Location of publication of the documents found for literature review of the classic car market

By reviewing and analysing the information of the records, 4 different themes were identified which are presented in Table 2.2. The allocation of articles to the relevant topic led to double allocation if the same article addressed two different contexts. Most literature found regarding classic cars was written in the context of classic cars as a marketing opportunity for car manufacturers. Three articles were investigating classic cars as an asset for investments. The longevity of cars was analysed by only one article and three articles mentioned the proportions of the classic car market. In step 5, the content of the records to each coding group is summarised.

Table 2.2: Mapping of the documents according to their context in the literature review of the classic car market

Context	***Records***
Classic cars as a marketing opportunity for car manufacturers	(Ebel and Hofer, 2014) (Hamilton and MacAuley, 1998) (Nieuwenhuis, 2008) (Bruls, 2017)
Classic cars as investment	(Bruls, 2017) (Dhont, 2017) (Hoffmann, 2018)

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Longevity of cars	(Hamilton and MacAuley, 1998)
Proportions of classic car market	(*Classic Car Market Review*, 2019) (Michael Kaiser, 2018) (KBA, 2020)

Step 5: Collate, summarise, and report the results

Classic cars as a marketing opportunity for car manufacturers

Classic cars represent the history of car manufacturers. Well maintained and restored vehicles are used by automotive companies to suggest the feeling of quality because their cars can last for a long period of time. Car manufacturers use classic cars events to present their aged cars and simultaneously present their newer or concept models. The idea behind this marketing strategy is that customers associate the durability of classic cars with the new car generation of the brand (Ebel and Hofer, 2014; Nieuwenhuis, 2008).

Car manufacturers are using classic cars for marketing purposes to benefit other company segments, but the restoration and maintenance of customers' cars is also a profitable business opportunity (Bruls, 2017; Nieuwenhuis, 2008). For this reason, car manufacturers shifted their mark-up on new cars towards the aftermarket segment with spare parts and services (Hamilton and MacAuley, 1998). To increase the profit on the aftermarket segment of classic cars, most car manufactures have founded a classic car department. Ferrari, Porsche, Audi, Mercedes and BMW are some of the manufacturers who offer services and products like spare parts, owner's manuals, model cars and originality certificates (Ebel and Hofer, 2014).

Classic cars as an investment

Most literature considered classic cars as in the context of an investment item. Classic cars fall into the category of "passion investments", along with wine, works of art and jewellery (Bruls, 2017; Hoffmann, 2018). Calculating the value of a classic car can be ambiguous and difficult since every car is a unique item. Nevertheless, the price of a classic car is influenced significantly by the three factors: rarity, condition, and history of the car (Hoffmann, 2018).

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Investments in classic cars can be made in several different ways. One such way is a direct investment via a private purchase of a classic car, the other is to invest indirectly via funds or certificates. With indirect investments, customers have the option to invest in a portfolio of multiple cars. The DOX (Deutscher Oldtimer Index) for example, developed by the German Association of the Automotive Industry in 1999, is based on the performance of 88 vehicles and recognised a significant increase since its foundation (Hoffmann, 2018).

Dhont (2017) analyses the risks and opportunities of investments in classic cars. The classic car market is a very volatile market, which offers investors high potential in return, but also a high risk of decreases in prices. Consumers are advised to diversify investments into a variety of different cars (Dhont, 2017). Furthermore, classic cars are one of few investments which provide usability. About a fourth of classic car owners in Germany see their classic car primarily as an investment item (Hoffmann, 2018). The ownership of an old car, however, also requires maintenance costs, such as storage, service and licensing (Dhont, 2017). Especially the cost for spare parts can shrink the return on investment drastically (Hoffmann, 2018).

Longevity and sustainable car use

The average life expectancy of a car has increased by 30 percent (from 5.6 years to 7.2 years) from 1969 to 1991. This trend is predicted to continue as a result of an increase in competition (Hamilton and MacAuley, 1998). Hamilton and MacAuley (1998) developed a “Scrapage Model” to illustrate the nature and size of possible improvements in longevity. In general, the automotive longevity depends on three factors: “price of new cars, the inherent durability of cars and the price of repair and maintenance parts”. A 60 percent decrease in spare part prices, for example, would lead to an increased longevity by 2 years. Even though the study of Hamilton and MacAuley (1998) was published in 1998, the developed model is considered in this literature review.

Classic car market properties

The “Federal Motor Transport Authority of Germany (KBA)” publishes a report once a year about the number of cars registered with a variety of different statistical characteristics. The number of registered cars, in conjunction with the statistical characteristic, “year of production”, can be used to analyse the trend of the classic car inventory in Germany. In 2010, the number of cars in Germany

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with an age of 30 years or older was at 356,916. This number of historic automotive vehicles increased by 271% to 970,221 in 2020. This growth is also recognized in the average age of all vehicles registered, which grew in a period of ten years from the average of 8,1 years (2010) to 9,6 years (2020) (KBA, 2020).

"AXA XL Art & Lifestyle Insurance" publishes their Classic Car Market Review on a two years basis and provides information and data of the classic car market, based on a "Database of over 155,000 sales records form auction houses worldwide" (*Classic Car Market Review*, 2019). The Classic Car Market Review (2019) estimates the number of classic cars in the USA at about 6 to 7 million for 2018, which makes it the largest market. Europe is following with 4.8 million collectable cars, with the majority of these cars located in Germany (1.5 million), France (1.1 million) and Italy (1 million). The Classic car Market Review (2019) categorizes classic cars according to their value. The Small Cap Index consists of classic cars with a value of under 100,000 Euros, while the Mid Cap Index includes classic cars with a value between 100,000 Euros and one Million Euros, and the Top Lot Index with values above one million Euros. The turnover and the number of cars sold were monitored from 2006 to 2019. All three indices show an increase in turnover over this period. The turnover of the Small Cap Index increased by 200%, while the number of cars increased by 430%. The Mid Cap Index´s turnover and number of cars sold statistics grew simultaneously. The number of cars sold in the Top Lot Index increased to about 400%, while the turnover only increased to 300%. By comparing the number of cars sold with the turnover of the three sectors, the Top Lot Index represents about 5% of the cars sold in the classic car market but created 30% of the total turnover. The Mid Cap Index represents about 15% of the classic cars while it contributed to 45% of the turnover. In contrast, the Small Cap Index represents 80% of all analysed classic cars, but these cars only had a 25% share in turnover (*Classic Car Market Review*, 2019).

The Classic Car Market Review (2019) also analyses the turnover of classic car sales according to their age, in 2008 and 2018. Figure 2.9 shows that in 2008, the largest percentage of the total turnover was created by classic cars between the age of 44 to 62 years (32%) and 34 to 43 years (29%). All classic cars built before 1945 contributed 18% to the total turnover. Like the market figures of 2008, the figures from 2018 shows that classic cars built between 1946 and 1974 have a main share in the total turnover, contributing to 43% of the total turnover. This percentage contributed to the total turnover would have been on the same level in 2008 if so called "Instant Classic Cars"(build between 1998 to 2018) and "Post Modern Cars" (build between 1988 to 1997) had been excluded from the statistic (*Classic Car Market Review*, 2019).

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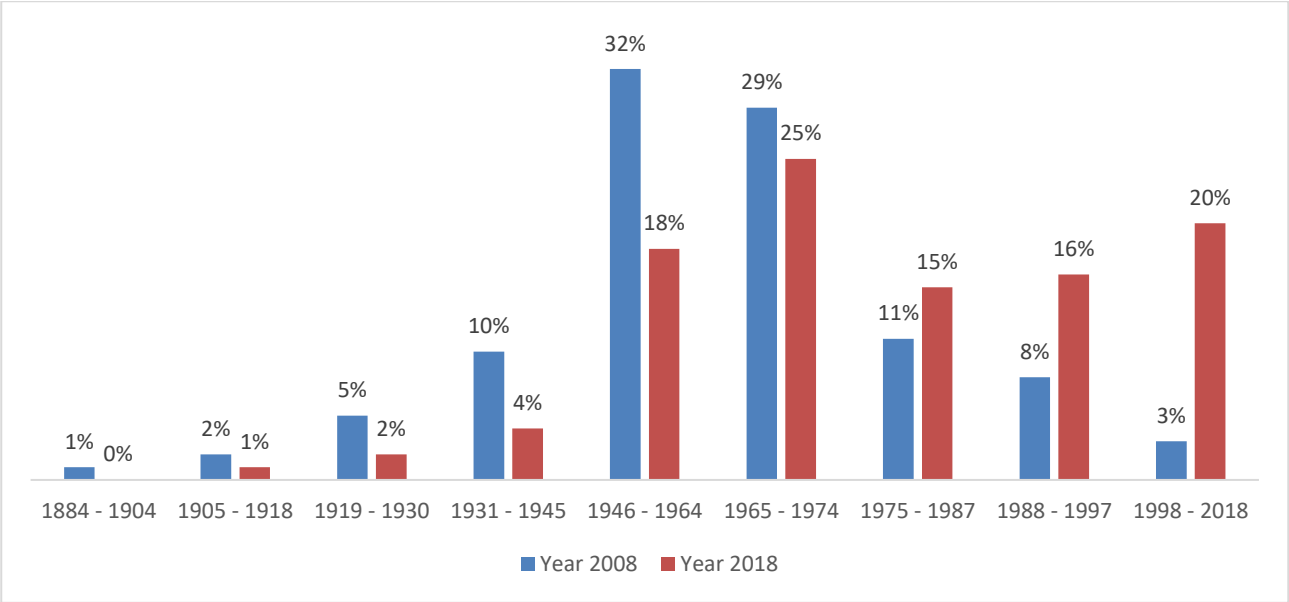

Figure 2.9: Market turnover by period built 2008 vs. 2018, adapted from (*Classic Car Market Review*, 2019))

In contrast to the Classic Car Market Review (2019), which included data based on sales via auction, Michael Kaiser (2018) published data from a market survey on behalf of the "German Association of the Automotive Industry (VDA)" which reviews the ownership and handling of classic cars and motorbikes in Germany. In this market survey, two different sample groups were considered. The first sample group were people who own at least one classic car (753 participants), and the second sample group represented the average population (1,407 participants). The report of the market survey from Michael Kaiser (2018) analyses six main topics of which 4 relates to the classic cars. These include the attitude of the participants towards classic cars, the ownership and usage of classic cars, the maintenance of classic cars, and the demographic trend of the Classic Car Group.

The main results of each topic from Michael Kaiser (2018) will be presented in the following:

The attitude of the population towards classic cars

- From 2008 to 2017: 9.1% decrease of interest in cars and 2.1% decrease of interest in classic cars. This is due to a difference in the usability of a car among people.
- 22% of all Germans were interested in classic cars or classic motorbikes, and 21% would have liked to own a classic vehicle. 30% of these people are under 30 years, and 14% over 60 years old.
- The main reasons for owning a classic car include the charm of classic cars (91%), receiving attention (69%), driving experience, and enjoying historic technical specifications (each 55%) and keeping a classic car as an investment (44%).

The ownership and usage of classic cars

- 70% of the classic cars registered in Germany were built in Germany.

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- The average age of a car owner is 50 years, the average age of a classic car owner is 55 years (in Germany).
- A historic car has been driven over an average distance of 1740 km per year (Total average of all cars: 12,508 km).

The maintenance of classic cars

- 62% of the classic car owners occasionally maintained their car themselves (in 2011), increasing to 68% in 2017.
- The main sources for spare parts include the Internet (71%), private contacts in the classic car scene (62%), specialised part dealers (60%), exhibitions or spare part markets (52%).
- The budgets per year for repairs on classic cars are primarily under 500 Euros (23%), between 500 and 1000 Euros (28%) or between 1000 and 2000 Euros (21%).

The demographic trend of the Classic Car Group

- 90.2% of classic car owners are male.
- The income of classic car owners is above the average in Germany. 14% of the classic car owners have a monthly income of over 6000 Euros (net income, in Germany)

Conclusion

In the process of the scoping review, literature was found that can be analysed in Porters Five Forces market model. Most information in literature is on the behaviour of buyers. Classic cars are mostly used as a hobby with the pleasures of driving and maintaining it. However, the market for classic cars as an investment is growing fast. The return on investment in this volatile market is, different to other investments, influenced by the costs for running and repairing the vehicle. The value of a classic car is determined by its condition and rarity. If the cost for maintenance exceeds the vehicle's value, it is likely that the vehicle gets scrapped. The costs and availability of spare parts are the critical factors regarding the future classic cars. Car manufacturers have recognized the growth of the classic car market and developed departments which offer sales of spare parts and services for their classic cars. The car manufacturer has the double advantage of having a profitable aftermarket segment and using their heritage fleet for marketing purposes of new models. Literature regarding the force "thread of new entrants" into the classic car market showed that two main entrants were discovered. Firstly, cars which are ageing are entering the market. With an increase in the longevity of cars, this number is growing constantly. Secondly, a trend is identified where cars are considered classic before they reach their age according to the definition of a classic car.

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Considering the information from literature regarding the first four forces of Porters market model, the fifth force, "Rivalry among existing Competitors", can be concluded as low. Each car manufacturer has his own classic car market with exclusive service and spare parts for that specific market. Furthermore, cars which are entering the classic car market should not be considered as a thread but more as an opportunity for manufacturers to increase their sales on spare parts for classic cars.

2.4 Spare part management in the automotive aftermarket

2.4.1 Introduction

"The main task of the spare parts management for long-living primary products is to guarantee an efficient spare parts supply beyond the end of serial production" (Schulze, Engel and Leichnitz, 2012). The automotive aftermarket is a broadly used term to describe the manufacturing, supply and fitting of spare and service parts needed after the initial sale of a vehicle, which also includes the restoration of classic cars and the customisation of vehicles (Reeves and Mendis, 2015). Therefore, the aim of this literature review is to analyse holistically the spare part management in the automotive industry, to then drive information on the niche market "classic cars".

Since many stakeholders are involved in the supply chain of spare parts in the automotive aftermarket, a framework is needed to analyse and model the process chain. Gaiardelli, Saccani and Songini (2007) analyses different supply chain performance measurement systems existing in literature. One of the models recommended is created by Chan (2003). His main objectives for performance measures are to increase resource efficiency, customer satisfaction and flexibility. In contrast to other models, Chan (2003) adds criteria like innovativeness, trust and visibility (Gaiardelli, Saccani and Songini, 2007). "From the management perspective, performance measurement provides the necessary information for management feedback to decision makers and process managers" (Chan, 2003). The performance measurement of a supply chain reflects the need for improvements and monitors the impact of changes made. With regards to the research topic of this project (the impact of additive manufacturing on the supply chain of spare parts for classic cars), the supply chain performance measurement system of Chan (2003) was identified as the best suitable framework. His system is explained in the following chapter.

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2.4.2 Supply chain management framework

The framework of Chan (2003) is based on seven main quantitative and qualitative measurements with several sub criteria (Table 2.3). For the analysis of the spare part management in the automotive industry, customer satisfaction is the main criteria of performance in the strategic objectives. Therefore, the supply chain analysis will be conducted with the focus on the end-consumer of the spare part.

Table 2.3: Outline for all performance measurements, adapted from Chan (2003)

Cathegory	Sub criteria level 1	Sub criteria level 2
A. Quantitative	Cost	Distribution, manufacturing, warehouse
	Resource utilisation	Labor, machine, energy
B. Qualitative	Quality	Customers dissatisfaction, customers response time, stockout probability, accuracy
	Flexibility	Output-volume, output-variety, modifications, new products
	Visibility	Time, accuracy
	Trust	Consistency
	Innovativeness	New launch of products, new use of technology

The performance measures are split into quantitative and qualitative measurements. Quantitative measurements, like cost and resource utilisation, are clear to measure and to interpret. “Cost should be kept as low as possible while resources should be kept at an optimum amount for effective use” (Chan, 2003).

Qualitative measurements, on the other hand, are more conceptual and need to be defined for its use as performance measurement. Quality as the first measurement, is closely related to customer satisfaction and can be measured by a variety of different subcategories. Customer satisfaction, for example, can be measured by looking at the level of customer dissatisfaction and the percentage of complaints. Other measures are mostly related to the delivery capability, delivery time and the accuracy of the delivered product according to specifications.

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The measurement of the flexibility of a supply chain is a widespread topic. Flexibility is commonly defined as the adaptability of a system or company to diversity or change. Measurements can be categorised into the flexibility of input (labour and machine flexibility), process (operation and material flexibility), output (volume, product variety and delivery flexibility) and improvement (modification, new product, and expansion flexibility). All subcategories of measurements are seen as positive, if the system or company can respond quickly to changes without incurring high cost or large changes in performance outcome.

The measurement visibility of a supply chain in Chan (2003) performance measurement model is defined by the accuracy and time in which information can transmit through the tiers of the supply chain. "Trust is the reliability and consistency between different levels of the supply chain and enhances the long-term relationship between them". Reliability and consistency in a supply chain are measured by delivery time and accuracy of materials and flow of information between the tiers of the supply chain.

The innovativeness in a supply chain can be important for gaining competitive advantage in an industry. Innovativeness can be enhanced in two ways, by the number of new products launched, and the usage of new technology. New technology can not only be applied on a physical product, but also on management methods. "However, new technology is difficult to measure directly. Thus, the percentage - increase in efficiency can be measured directly, by measuring the percentage - decrease in time necessary for producing the same product" (Chan, 2003).

Each of the given performance measurements contribute to the overall performance of the supply chain. However, each industry has different perceived levels of importance for each category. Therefore, every measurement receives a weighting according to the specific industry characteristics. The presented supply chain performance measure system will provide a framework for the following scoping literature review.

2.4.3 Literature review – spare part management

The literature scoping review on the subsection "spare parts in the automotive industry" covered three main topics. Firstly, different approaches for the classification of spare parts are presented. Then, literature existing on the management of spare parts is analysed. Lastly, literature regarding the spare

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part management of spare parts is analysed to provide information for the analysis of the supply chain performance model.

Step 1: Identifying the research questions

The success of using AM to produce spare parts for classic cars was measured by the competitiveness of spare parts on the market. Limited literature was published on the spare part supply of classic cars. By analysing the literature published on the spare part supply of general cars, the market properties of spare parts for classic cars were accessed. The following research questions addressed the current supply of spare parts in the classic car industry:

Research Question 1	Which types of spare parts exists and how can they be classifyed?
Research Question 2	How is the performance of the spare part management for classic cars rated?
Research Question 3	Which spare part management characteristc does classic cars have?
Research Question 4	Which strategies are recognized in the spare part management of classic cars ?

Step 2: Identify relevant studies and statistics

As in the first literature review in Chapter 2.3, the scoping review of Arksey and O'Malley (2005) was utilized. Basic exclusion criteria based on the date of publication were not given. Literature from the decades when classic cars were built might have influenced the spare part supply nowadays. All sources written in English and German were considered. The final search strategy included the e-Databases Wiley, Science Direct and Springer Link. The three e-Databases were identified to have the most documents suitable and provided enough records to cover the relevant topics. Furthermore, the e-Databases were accessed through the membership of “University of Stellenbosch” and “Hochschule München” to expand the accessible literature.

Searching was executed using the following three search strings in English:

- “Spare part” OR “Genuine parts” OR “End-of-production OR “Aftermarket” AND “Classification” AND “Automotive” OR “Classic car”.
- “Spare part” OR “Genuine parts” OR “End-of-production OR “Aftermarket” AND “Management” OR “Obsolescence” AND “Automotive” OR “Classic car”.

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- “Spare part” OR “Genuine parts” OR “End-of-production OR “Aftermarket” OR “Classic car” AND “Supply chain” OR “Distribution” OR “Manufacturing” AND “Automotive” OR “Classic car”.

The corresponding search strings in German are as follows:

- “Ersatzteil” OR „Verschleißteil“ OR „Verbrauchsteil“ OR „Nachserien“ OR „Ersatzteilmarkt“ AND “Klassifizierung” AND “Automobil“ OR „Oldtimer“.
- „Ersatzteil“ OR „Verschleißteil“ OR „Verbrauchsteil“ OR „Nachserien“ OR „Ersatzteilmarkt“ AND „Management“ OR „Planung” OR „Obsoleszenz” OR „Veralterung“ AND „Automobil“ OR „Oldtimer“.
- „Ersatzteil“ OR „Verschleißteil“ OR „Verbrauchsteil“ OR „Nachserien“ OR „Ersatzteilmarkt“ AND „Lieferkette“ OR „Supply chain” OR „Fertigung” AND „Automobil“ OR „Oldtimer“.

Step 3: Select studies and statistics

The PRISMA-ScR flow diagram was used as a template to illustrate the record selection process for the review (Figure 2.10). In the Identification phase 236 records were found in the three electronical databases. The title and abstracts of these records were screened in phase two. In this phase, 173 records were excluded because their content did not suit the research questions of this literature review. The resulting 63 records were assessed, in the third phase, in a full-text analysis to identify whether the content is contributing towards a base of knowledge, or whether the record has to be excluded. In the last phase, the remaining 16 records were analysed for the inclusion in this scoping literature review.

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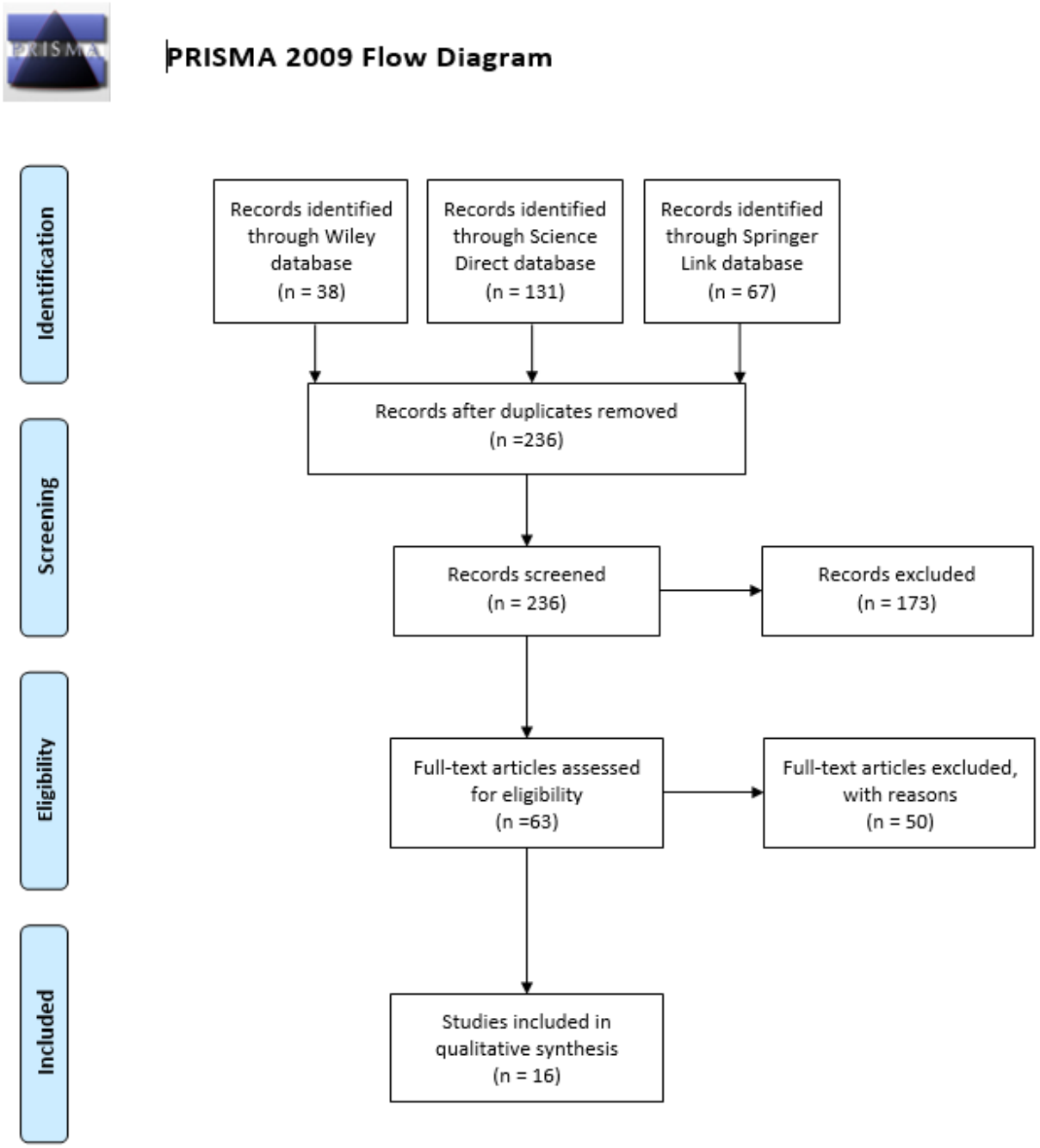

Figure 2.10: PRISMA-ScR Flow Diagram for the literature review of the spare part management in the automotive industry, adapted from Rouse (2016)

Step 4: Chart the Data

The data and information will be extracted from all studies identified as relevant. A logical and descriptive summary will be presented to answer the research questions for this chapter (Peters *et al.*, 2015). All publications addressing issues of the spare part management in the automotive industry were considered without limitation to the year of publication. The documents were categorised according to codes as listed in Table 2.4 by using the qualitative data analysis software "ATLAS.ti". The following codes were used to categorise the content and characteristics of the documents:

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Table 2.4: Categories for the analysis of literature in the spare part management literature review

Coding Groups	***Codes***
Paper characteristics	• Title • Year of publication • Location of publication • Geographical focus • Industry focus • Publication database • Publication type
Spare part classification	• Definition • Classification models
Spare part management	• Definition
Spare part supply chain	• Supply chain design • Aftermarket suppliers • Distribution strategies • Inventory management
Spare part planning	• Definition • Automotive life cycle • Spare part demand forecasting • Predictive maintenance • Obsolescence
Spare part production	• Final order • Remanufacturing

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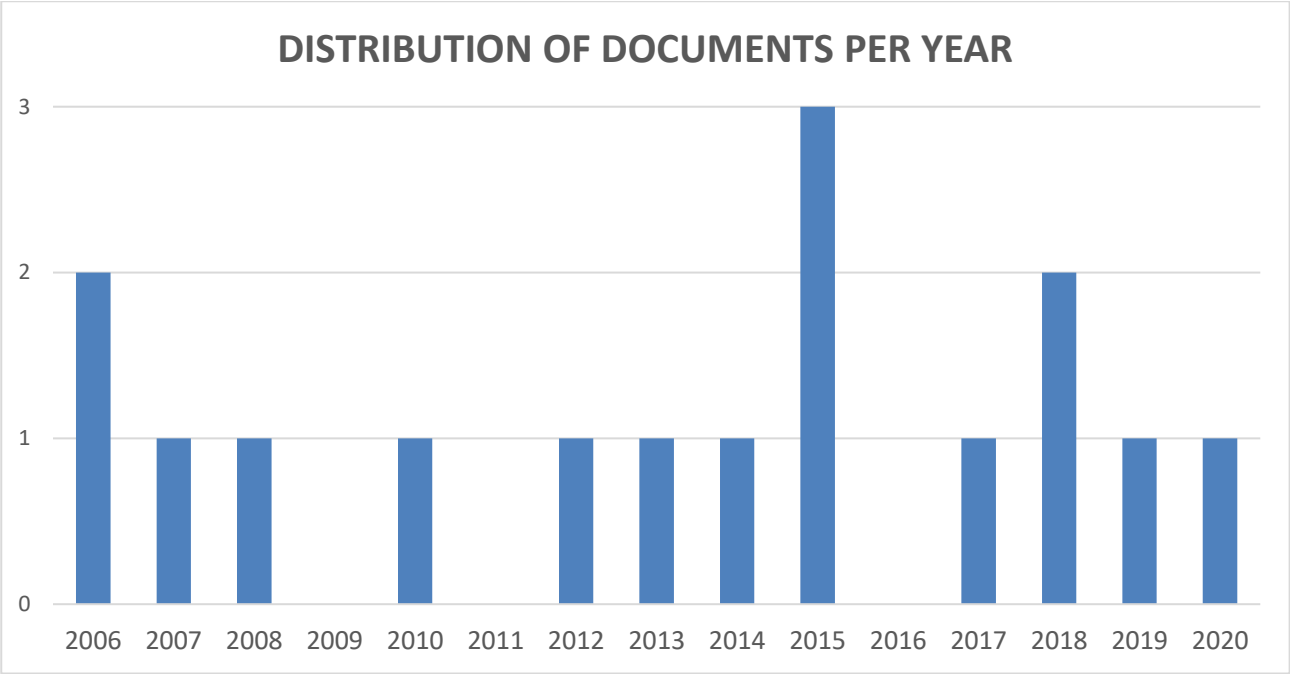

Figure 2.11: Distribution of documents per year for the literature review of the spare part management in the automotive industry

The charting of the literature according to the year of publication indicates that spare part management received constant attention in literature in the near past (Figure 2.11). The fact that no literature found was older than 2006, might be due to the non-digitalisation of older sources. Additionally, the analysis of the documents revealed that four out of the five oldest documents were published in books (Figure 2.12). Considering Figure 2.12, most documents found for this scoping review were published as book sections. Five out of the six book sections were published by Springer. On the other hand, Wiley and Springer have the main shares in Articles/Papers and Journal Articles published. Consequently, all Conference papers were published by Science Direct.

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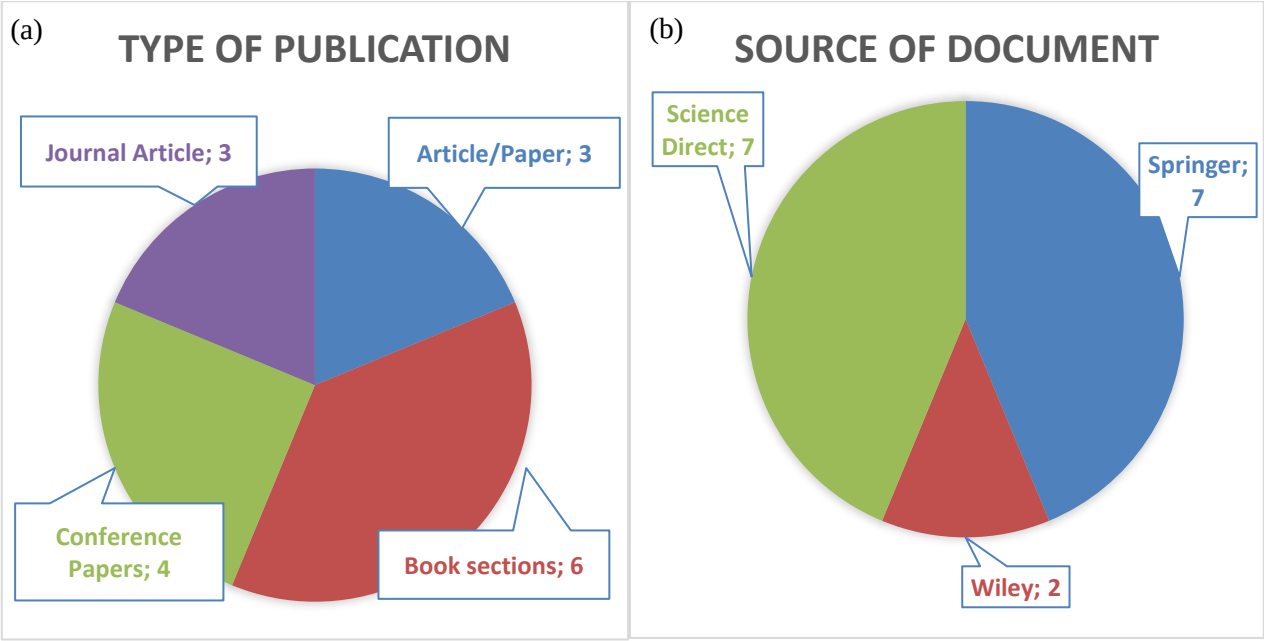

Figure 2.12(a) and (b): (a)Type of publication of the documents found for the literature review of the spare part management in the automotive industry; (b) Sources of the documents found for the literature review of the spare part management in the automotive industry

Figure 2.13 shows that half of the documents were published in Germany, while the second half of publication is equally distributed between seven nations all over the world. Although eight documents were published in Germany, only two of them focus on the spare part management in Germany. The majority (75%) of publication does not focus specifically on one nation. In addition, only two publications were written in German, all remaining publications are in English.

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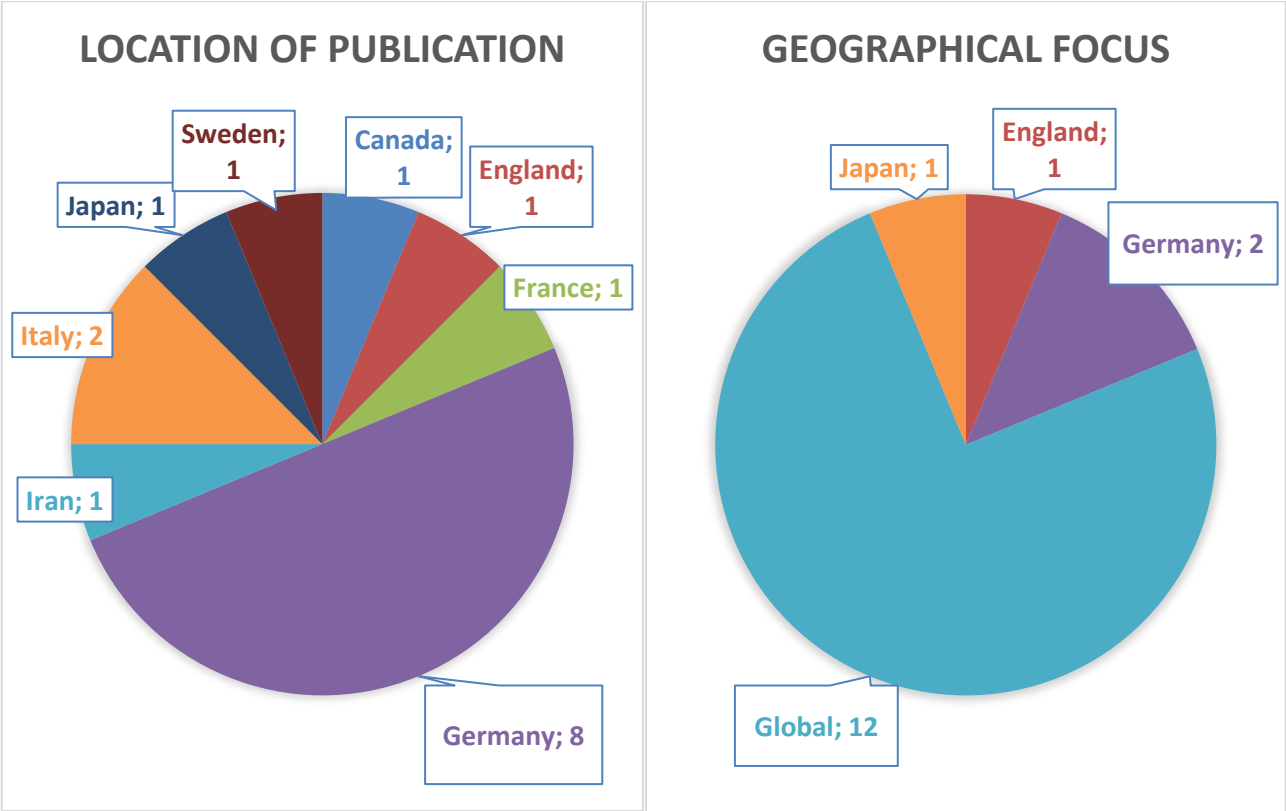

Figure 2.13 (a) and (b): (a) Location of publication of the documents found for literature review of the spare part management in the automotive industry; (b) Geographical focus of the documents found for the literature review of the spare part management in the automotive industry

Although all search strings included the topic "automotive vehicle", two documents were included in the literature review which are not relative to the automotive Industry (Figure 2.14). These two documents are book sections describing the general spare part management of industrial goods. Apart from these documents, a further five documents review the automotive industry and at the same time either the electronic, or the industry in general. The large number of publications comparing the automotive industry to other industries is seen as evidence for the entry of the two book sections describing the spare part management of general industrial products.

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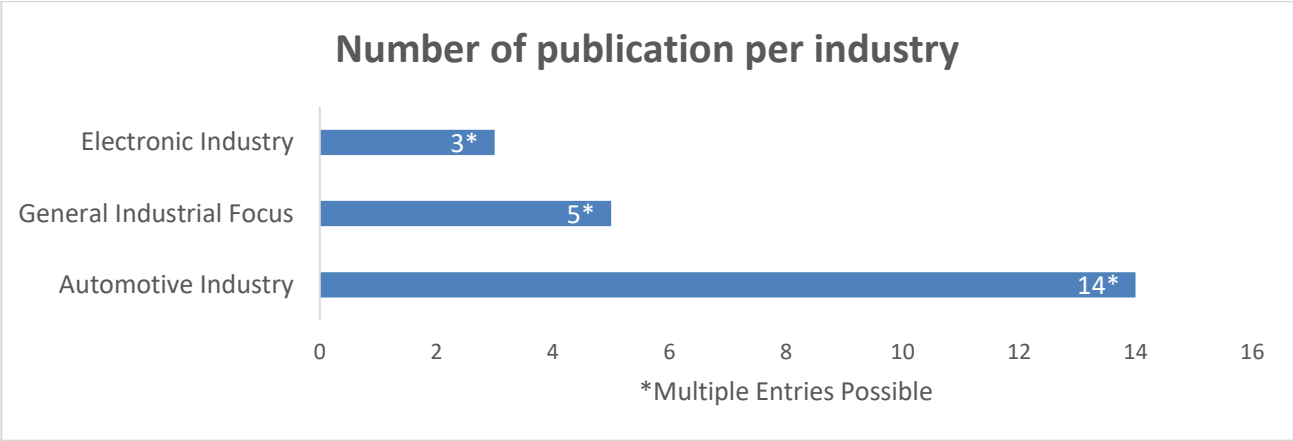

Figure 2.14: Number of publications per industry in the literature review of the spare part management in the automotive industry

By reviewing and analysing the information of the records, four main coding groups were identified which are presented in Table 2.5. Most records found were analysing the three sub-topics of the spare part management. In addition, three articles were classifying spare parts of the automotive industry. The allocation of articles to the relevant groups led to double allocation if the same article addressed two different contexts. In step 5, the content of the records to each coding group is summarised.

Table 2.5: Mapping of the documents according to their context in the literature review of the spare part management in the automotive industry

Coding groups	***Records***
I. Spare part classification	Kampschulte (2017); Mehdizadeh (2020); Schröter (2006);
II. Spare part management	Schröter (2006)
a. Spare part supply chain	Gaiardelli, Saccani and Songini (2007); Klug (2010); Loukmidis and Luczak (2006); Mehdizadeh (2020); Ronzoni, Ferrara and Grassi (2015); Smith *et al.* (2019);

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b. Spare part planning	Boissie *et al.* (2018); Dombrowski and Engel (2014); Dombrowski and Schulze (2008) Klug (2010); Loukmidis and Luczak (2006); Schröter (2006); Schulze, Engel and Leichnitz (2012);
c. Spare part production	Casper and Sundin (2018); Dombrowski and Schulze (2008); Guidat *et al.* (2015); Ikeda (2017); Inderfurth and Kleber (2013); Klug (2010);

Step 5: Collate, summarise, and report the results

I. Spare part classification

Mehdizadeh (2020) analyses the inventory control systems of distributors in the supply chain of automotive spare parts to improve its effectiveness. "A proper classification would make a significant improvement in choosing the appropriate policy to control the inventories of each group" (Mehdizadeh, 2020). The method he chose for the classification of spare parts, is the ABC-analysis. His literature review highlights that the value of demand is the most common parameter to conduct an ABC-analysis. However, literature was found that utilises other criteria. These criteria are for example "substitutability, obsolescence, commonality, lead time, reliability and criticality" (Mehdizadeh, 2020).

With regards to the ABC-Analysis of spare parts, especially when using the value of demand, the research of Kampschulte (2017) might have an impact on the process and results of the analysis. His work researches the modular standard in the automotive aftermarket, in particular shock absorbers. One example shows that one car manufacturer platform is used in 13 different car models with 22 different suspension kits. By grouping the part numbers of the suspension assembly by parameters and measures into component classes, the number of kits provided for this platform could be reduced from 22 to 7 kits (Kampschulte, 2017). This analysis shows that one spare part can be used for more than one model, especially when the models are sharing the same model platform. This fact must be considered when analysing the value of demand for spare parts.

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Schröter (2006) uses an additional method for the categorising of spare parts. Spare parts are defined by the DIN-Standard 24 420 "Lists of Spare Parts" as parts or assemblies which are used to replace worn, broken or missing parts or assemblies. Three categories of spare parts resulting from that definition are based on the reason for replacement (Figure 2.15). Firstly, parts which need to be replaced because their service life exceeded. Secondly, parts which wear by using the product in which they are installed, and lastly, parts with a weak link which break under overload (Schröter, 2006). In addition, accessory parts can be defined as an alternate class of spare parts (Figure 2.15). Accessory parts are components which change or expand the function or appearance of a product (Schröter, 2006). Furthermore, spare parts are also categorized by their origin. Three different origins of spare parts were defined (Figure 2.15). Firstly, spare parts produced by the serial manufacturer or its suppliers, so called original parts. Secondly, spare parts which are imitations of the original part, produced by suppliers of the serial manufacturer or companies who are recreating parts. Lastly, parts which are used and re-manufactured to its original functionality.

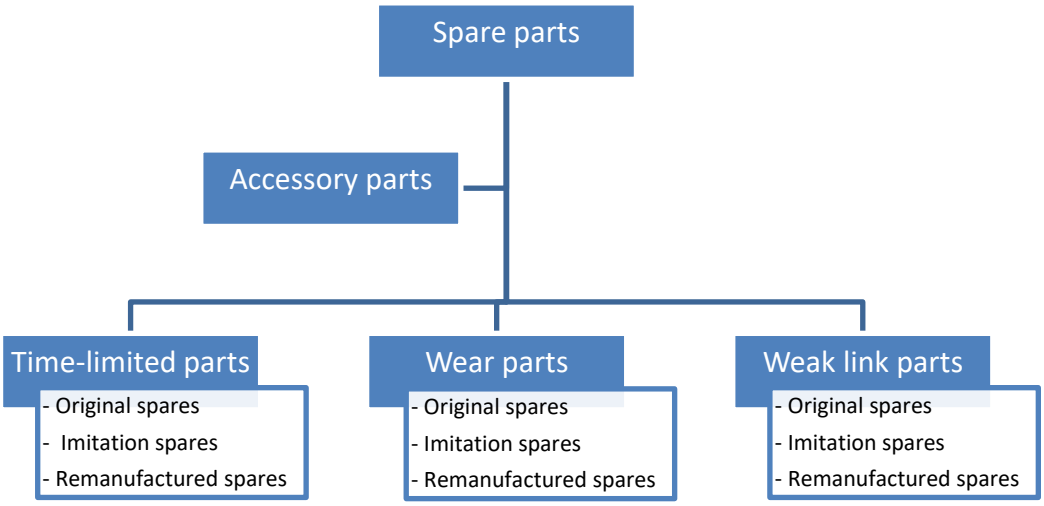

Figure 2.15: Ways to classify spare parts, information from Schröter (2006)

II. Spare part management

"It is the responsibility of spare parts management to carry out all business management tasks related to the procurement of input materials for the production of spare parts, the production of the spare parts themselves and the distribution of spare parts" (Schröter, 2006). A distinction must be made between the spare parts management of the supplier, and the spare parts management of the customer. The main goal of spare parts management by the customer is to maintain the goods used by him through the services with the required spare parts. In contrast, the goal of the supplier's spare parts

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management is to plan, manage and control the supply of spare parts to customers. In the following section, the focus will be on the supplier's spare parts management (Schröter, 2006). Based on this definition, the literature review of the spare part management in the automotive industry is split into three subsections. The subsection "a" will present literature regarding the market players and the distribution channels of spare parts. In subsection "b", topics affecting the planning of spare parts over the life cycle of a car will be addressed. Adding on to the results of the planning of spare parts, different strategies of producing spare parts will be addressed in the section of coding group "c".

a. Spare part supply chain

A number of records models the supply chain of spare parts and after sales services in the automotive industry with similar results. After giving an overview of the supply chain by reviewing the supply chain map of Gaiardelli, Saccani and Songini (2007) (Figure 2.16), information from other literature will be added.

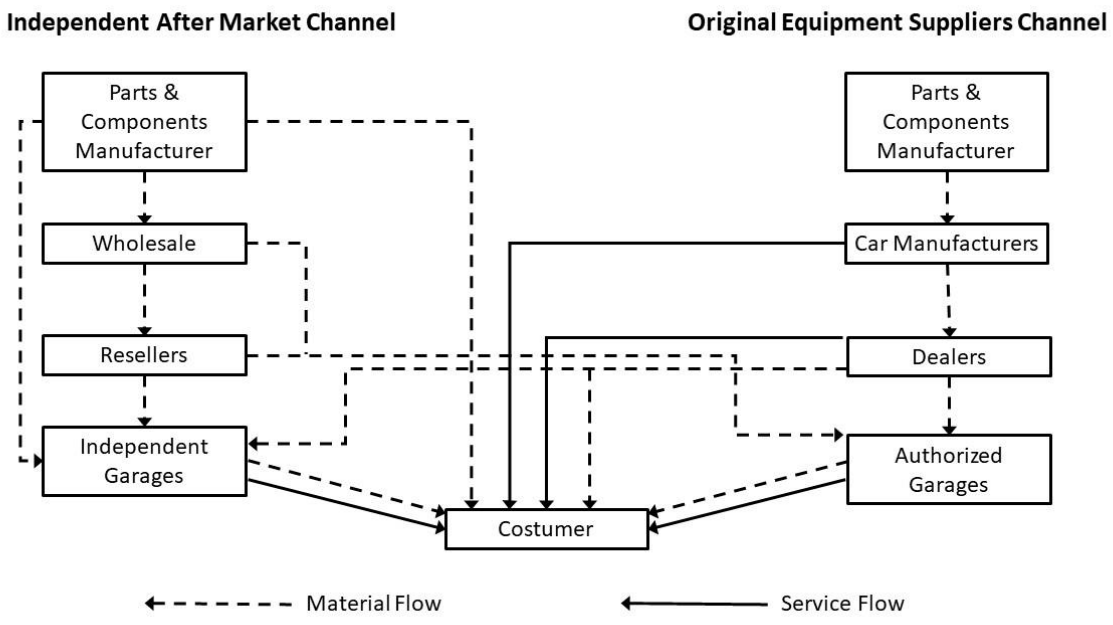

Figure 2.16: The after-sales supply chain for the automotive industry, adapted from Gaiardelli, Saccani and Songini (2007)

Figure 2.16 shows the main actors in the after-sales service chain. Apart from the supply chain of spare parts (Material Flow), the supply of service is mapped as well (Service Flow). Parts and component manufacturers sell their spare parts in both the Independent Aftermarket and the Original Equipment Suppliers Channel. Car manufacturers usually buy spare parts from suppliers and distribute them to authorised dealers and garages. The customer can choose between the two channels.

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An exchange of spare parts between the two channels at company level is possible (Gaiardelli, Saccani and Songini, 2007).

Ronzoni, Ferrara and Grassi (2015) map a similar supply chain design. Their supply chain analysis focuses on spare parts with slow moving and infrequent demand in the independent aftermarket. Parts from this channel are primarily used for old cars with an expired warranty. The problem of spare parts with these demand characteristics is that distributors (wholesalers, resellers, and dealers) cannot place large orders with suppliers to receive a price discount, which results in high inventory costs. In addition to this, stock must be kept to avoid lost sales. Moreover, the same spare part is stored at multiple distributors. Ronzoni, Ferrara and Grassi (2015) have created a mathematical model in combination with a platform where distributors can network so that only one distributor can store the product while still making it available for other players. The aim of this business model is to reduce inventory costs while maintaining the same service level (Ronzoni, Ferrara and Grassi, 2015).

Loukmidis and Luczak (2006) focus on the different roles of spare part suppliers in the after-sales supply chain. Four types of spare part suppliers were identified:

- Type 1a: Companies are part manufacturers and supply their customers with original or replica parts without being the primary product manufacturer themselves.
- Type 1b: Companies are primary product and part manufacturers at the same time and supply their customers with original parts.
- Type 2: Companies are service providers who take on the supply of spare parts for their customers and can customize their service portfolio from procurement, storage, planning, delivery, maintenance to complete service for their customers.
- Type 3: Companies are the operators (users) of the primary products and are responsible for supplying spare parts as part of their maintenance.

Type 1a and Type 1b are manufacturers of spare parts to supply their after-sales service. The aim of Type 2 companies is to procure and supply spare parts to their customers, which are workshops or other spare part suppliers. The objective of Type 3 companies is to maintain their own products.

As mentioned in section “I”, Mehdizadeh (2020) classifies spare parts with the ABC- Analysis to improve the effectiveness of inventory control systems of spare part distributors. “Demand forecasting for a large number of auto spare parts at different levels of a decentralized supply chain is one of the most important, and at the same time, the most complex issues of managing this chain” (Mehdizadeh, 2020). Therefore, his research presents the ordering process in the supply chain.

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Demand for spare parts is initially created by the customer at the retailer´s location. The retailer searches via the part number or the vehicle identification number (VIN) to find a suitable spare. Parts available at the retailer can be sold immediately to the customer. Parts that are not available need to be ordered at the distributor. If the customer accepts the price and delivery time, the order will be placed at the distributor. The delivery time of the distributor is determined by whether parts are in stock or not. If a part is not in stock, the distributor must order the part from the supplier. Distributors and suppliers usually have a fixed lead time for most parts (Mehdizadeh, 2020). This analysis of the ordering process shows that spare parts can be classified into groups according to their urgent need. Spare parts with an urgent need will be kept in stock by the reseller and distributor to achieve customer satisfaction.

A publication of Smith *et al.* (2019) analyses open data sets from small and medium enterprises (SME) of the automotive aftermarket. The analysed data set included after extractions over 700.000 invoices which includes specific car-related detail. This data set provides a "complete record of when a part was bought, the quantity, and how many, if any, were returned." (Smith *et al.*, 2019).
The findings of the data analysis will be presented in the following:

- The return rate for a specific air filter shows a hyperbolic pattern of return rates at small quantities.
- The measurements of a specific fuel filter varied between suppliers. Only 11 out of 29 spare parts had the original measurements.
- The time for a replacement of a worn part is predictable. The plotting of a replacement of brake discs and the mileage of a specific model identifies when replacement is needed.

The given examples indicate the potential of additional services in the automotive aftermarket using data science. The varying measurements on the fuel filter highlight that "it is possible to find parts which can be applied to cars not previously considered, by matching measurements" (Smith *et al.*, 2019). The predictability of part replacements makes it "possible to provide a service to advise the second-hand vehicle market how expensive one particular vehicle make/model may be to repair and service during the car's life compared with other marks/models" (Smith *et al.*, 2019). The limited accessibility to data and the visualisation of the results were identified as the main obstacles of implementation data science in the automotive aftermarket (Smith *et al.*, 2019).

Klug (2010) describes the logistics chain of spare parts in the automotive industry. Due to a heterogeneous product mix, the author recommends an ABC-XYZ-Analysis for the disposition and

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supply of spare parts. The aim of this analysis is to determine the value share of goods stocked (ABC) and their regularity in consumption (XYZ). Further criteria like critical spare parts, the contribution margin per spare part, the nature of the spare parts and dangerous goods are implemented into the analysis in practice.

The ABC-XYZ-Analysis is the basis for the decision making of where to store spare parts. The whole spectrum of spare parts is stored in central warehouses, medium and fast-moving parts in regional warehouses and only the fast-moving parts are stored at local dealers. In Germany, most spare parts have a lead time of 24h. For this lead time, the local dealers have a level of service of 85%. Due to fast delivery services in the distribution chain, the service level increases to 98% by integrating the regional and central warehouses (Klug, 2010).

b. Spare part planning

"Demand for spare parts is required, if the serial product components differ from their original target state, e.g. due to wear and tear, random failure, or external influences" (Schröter, 2006). Most industrial products require spare parts in their life cycle. The market potential for a spare part is determined by the number of primary products in use in which the respective part is installed. The inventory of a primary product, in turn, depends on its cumulative sales figures. The primary product inventory shows the typical course of a product life cycle (Figure 2.17).

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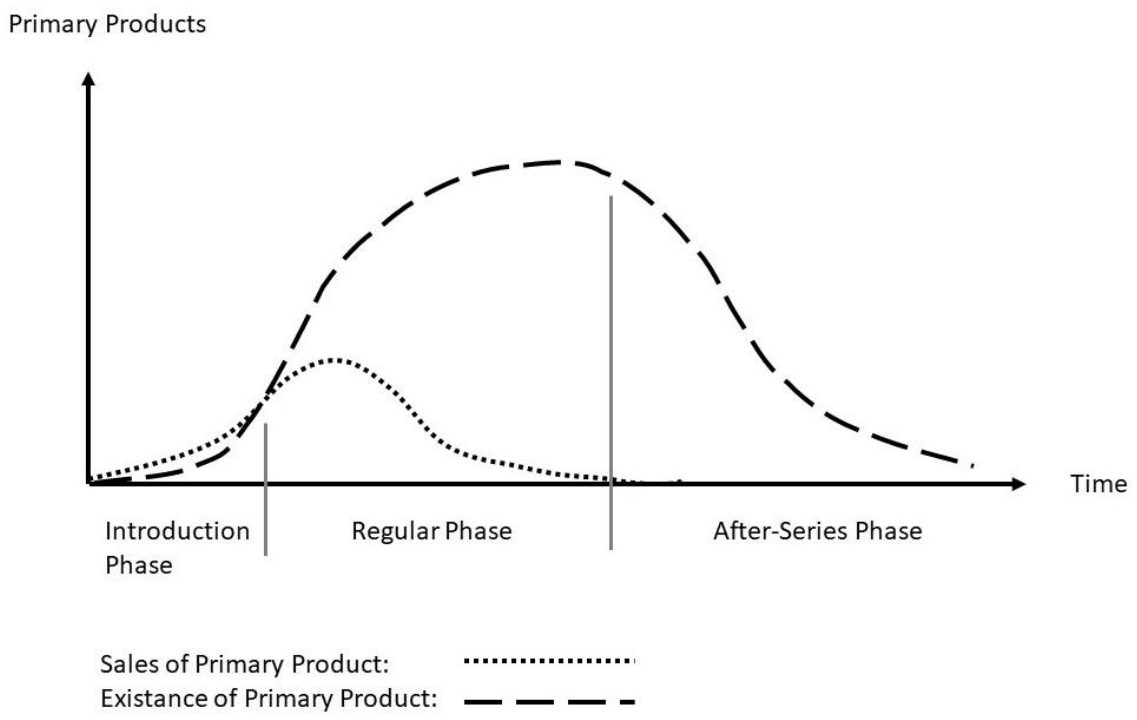

Figure 2.17: Market cycle and stock development of a primary product, adapted from Schröter (2006)

The demand for spare parts over the lifespan of an industrial component is strongly influenced by the condition and quality of the component as well as the type of primary product for which the spare part is used. Nevertheless, the spare part's life cycle can be divided into three phases based on the processes are shown in Figure 2.17 (Schröter, 2006):

I. The "Introduction Phase" of a spare part starts with the production of a new primary product. The main planning problem in this phase is to achieve a high level of service without having extensive knowledge of the failure behaviour of the spare part and the resulting demand.
II. In the regular phase, a larger number of primary products are already in use for a long time. As a result, the manufacturer has some experience of the demand for spare parts and is, therefore, able to carry out more precise demand forecasts.
III. The post-series phase extends from the point at which production of the primary product is stopped, until the end of the manufacturer's last spare parts supply obligation.

The model of Schröter (2006) for general industrial products can be identified in many other models analysing the demand of spare parts in the automotive industry. Klug (2010), Dombrowski and Schulze (2008), Loukmidis and Luczak (2006) and Inderfurth and Kleber (2013) conducted research on the demand of spare parts over the life span of automotive vehicles. All research reviews will be analysed sequentially in the following paragraphs. Only information which were not mentioned by, or which are contrary to previous analysed research, will be mentioned.

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Klug (2010) also separates the demand for spare parts over the lifespan of a car in three phases (Figure 2.18). The Serial Production Phase is characterised by a slowly increasing spare part demand caused by a few early failures. At the end of the first phase and during the second phase, the demand for spare parts is relatively constant. In the Outlet Phase, the car inventory is strongly decreasing, as is the demand for spare parts (Klug, 2010).

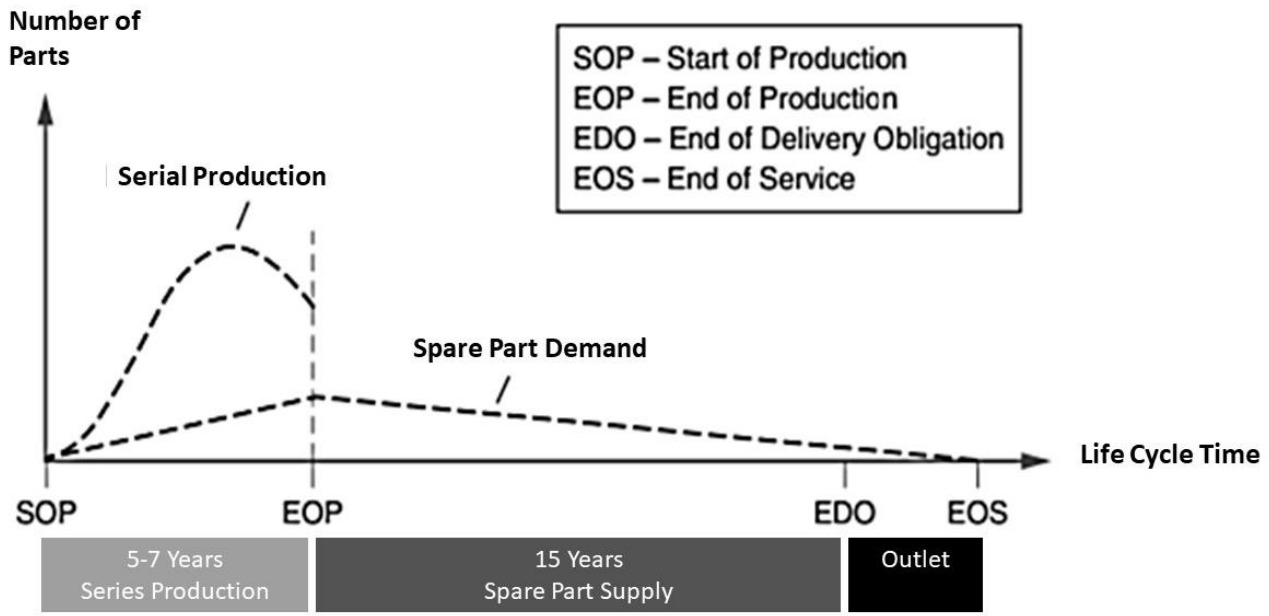

Figure 2.18: Demand for spare parts in different phases, adapted from Klug (2010)

By selling a new car, the automobile manufacturer undertakes to deliver spare parts during the vehicle customer's use phase. For legal reasons, automobile manufacturers are obliged to guarantee the supply of spare parts for their vehicles for up to ten years after series production has ended. The vehicle manufacturers often give a voluntary supply period of an average of 15 years after the end of production, depending on the respective vehicle type (Klug, 2010).

Dombrowski and Schulze (2008) reviews the demand of spare parts in two different groups (Figure 2.19). The first group are worn parts, which need to be replaced after a certain period. The approximate point of time for replacement is predictable. The second group has faulty parts. These parts are designed to last the entire life cycle of the product without failure. Even so, the part can fail due to external factors, such as an accident or to internal factors, such as manufacturing defects (Dombrowski and Schulze, 2008).

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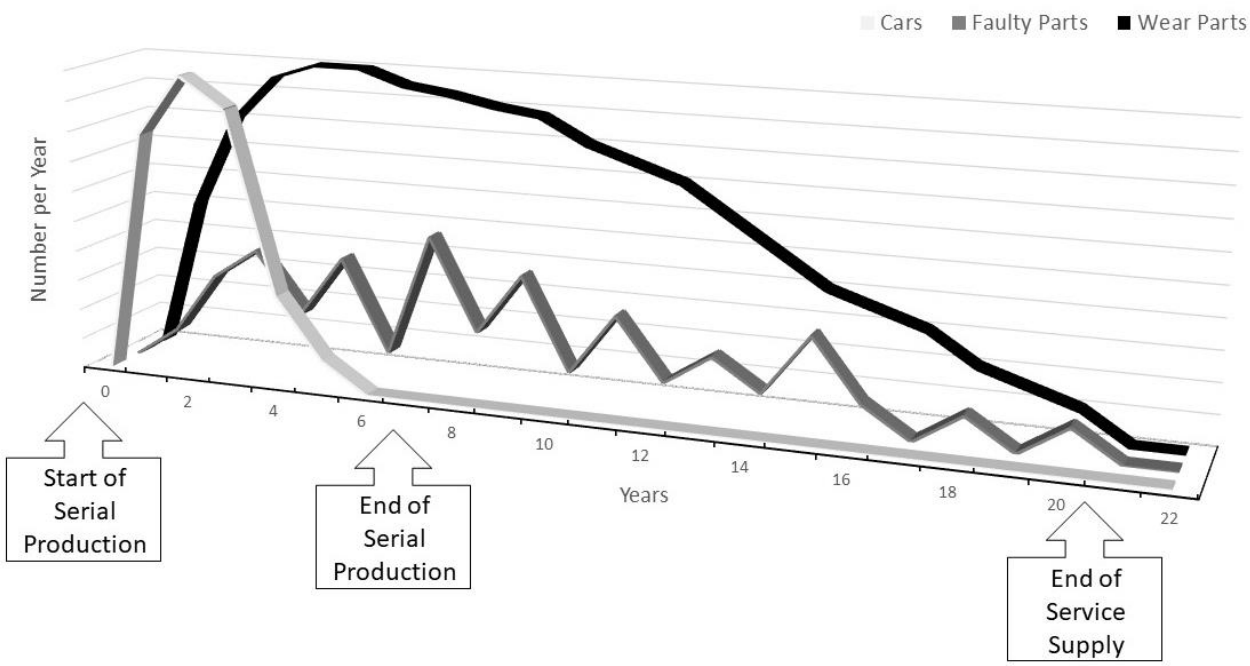

Figure 2.19: Demand trends for spare parts after the end of series production, adapted from Dombrowski and Schulze (2008)

Figure 2.19 shows, that wear parts have a high and constant demand. Therefore, wear parts are easily forecastable in the period between End of Serial Production and End of Service Supply. Since wear parts are usually suitable for extra-production, their post-series supply proves to be unproblematic. In contrast to wear parts, the demand caused by faulty parts is comparatively low and the time for replacement of faulty parts is difficult to predict. Despite these problems, however, these parts must be continuously available until the End of Service Supply (Dombrowski and Schulze, 2008).

Loukmidis and Luczak (2006) confirms the three-phase approach mentioned above. In addition, the researchers investigate factors that influence the demand of spare parts. The results show that the demand is influenced by many factors which can be grouped into four categories (Figure 2.20) (Loukmidis and Luczak, 2006).

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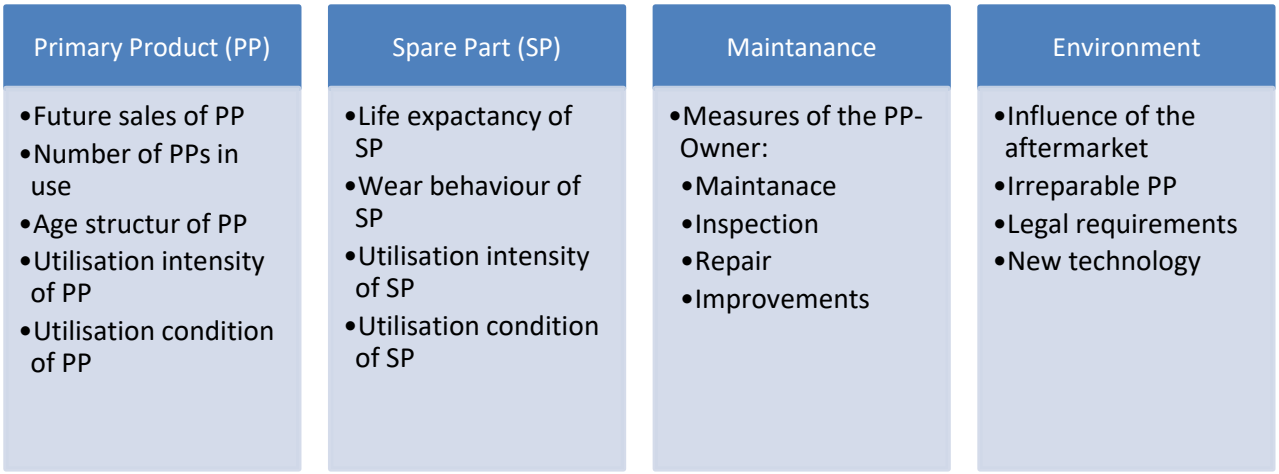

Figure 2.20: Influencing factors which affect the demand for spare parts, adapted from Loukmidis and Luczak (2006)

A demand for spare parts requires the usage of primary products. The more primary products that are available and used on the market, the higher the potential demand for spare parts. Additional factors which are related to the primary product, are the expected life expectancy and the resulting age structure of the car series. Furthermore, the way the primary product is used influences the demand. Like the life expectancy of the primary products, the service life of the spare parts plays an important role. An increased service life of spare parts leads to a lower demand. Factors such as wear behaviour, intensity of use and operating conditions also play an important role for the spare part itself (Loukmidis and Luczak, 2006).

According to DIN 31051, maintenance can be divided into the basic measure's maintenance, inspection, repair, and improvement. The usage of these basic measures in turn can be defined by 3 different strategies based on the damage, time, and condition. With the damage-based strategies, components are only changed in case of failure. The second strategy is based on time intervals. Parts are exchanged after defined time intervals, regardless of their condition. In contrast to this, the condition-based strategy is only based on the condition of the part, regardless of the time intervals. The time-based strategy is best for the predictability of demand. The damage-based strategy on the other hand, creates an unpredictable demand (Loukmidis and Luczak, 2006).

The last out of the four groups influencing the demand of spare parts, is hosting factors regarding the environment. The demand for spare parts is influenced by the available range of spare parts on the market, such as original parts or after-market parts. On the other hand, demand is also influenced by market external factors like legal requirements or the introduction of new technology (Loukmidis and Luczak, 2006).

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The technological improvement process and changes of the law can be reasons for the discontinuation of a product. The discontinuation of a product during the life cycle of the primary product, is called "Obsolescence". The obsolescence management in the automotive and other industries is the research area of the study from Schulze, Engel and Leichnitz (2012). "Obsolescence in this context means the end of availability of products, or the expiration of support of products by their original sources" (Schulze, Engel and Leichnitz, 2012). The discontinuation of a product can be caused by several reasons. In addition to the technology improvement process and changes in law, a discontinuation can be caused by changes in the market, such as the insolvency of enterprises.

Furthermore, the research of Schulze, Engel and Leichnitz (2012) focuses specifically on the obsolescence of electronic spare parts in the automotive industry. The major problem in the automotive industry is that the life cycle of a vehicle (24 years) is significantly longer than the life cycle of the embedded electronic components (3 years). The researchers identified an additional problem concerning obsolescence of electronic spare parts. Electronic components are part of an assembly group which belongs to the group of faulty parts. These spare parts have an unpredictable demand and long-term forecasts have therefore a high uncertainty. In addition to this, many electronic components, like sensors and photo resistors, have a limited storage life. To address these problems, the researchers presented an obsolescence management process which consists of four steps (Figure 2.21).

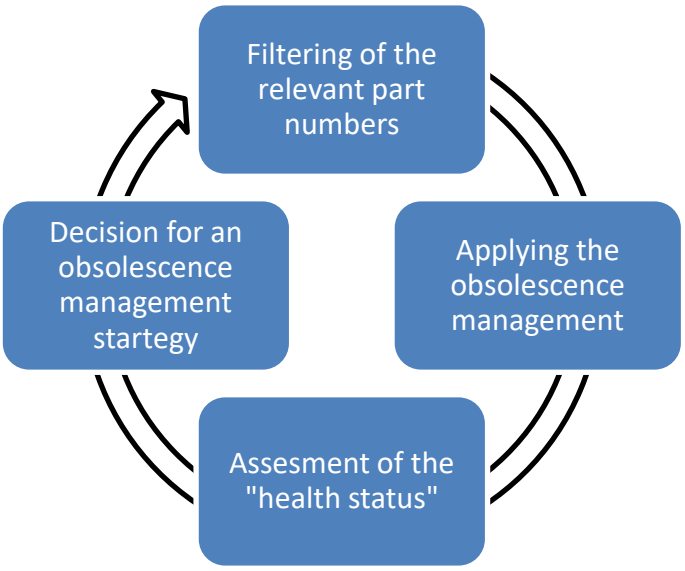

Figure 2.21: The four step obsolescence management process, adapted from Schulze, Engel and Leichnitz (2012)

The Four step obsolescence management process starts with the filtering of all spare parts of a company, in which all redundant and non-electronic parts are eliminated. In this case, parts are

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defined as redundant if an electronic element is assembled in several components. Step two consists of choosing the data source and the required data for the health status analysis. The databases can be built and maintained by the company itself, or the company can utilize the databases of obsolescence service providers. The third step utilizes the database to identify the health status of spare parts. The health status is calculated through the availability of the spare part on the market, the risk of discontinuation and the compatibility of other parts. In the final step of the process, an obsolescence strategy must be chosen in order to meet the challenge of obsolescence proactively. The researchers state that every strategy is dependent on company-specific factors. However, two general applicable solutions are recommended. Firstly, creating a continuous internal communication between the spare part management and the product development to avoid obsolescence of new products. Secondly, improving the relationship and communication network between the producing company and its suppliers to identify obsolescence risk earlier (Schulze, Engel and Leichnitz, 2012). As mentioned in the literature review of Schulze, Engel and Leichnitz (2012) spare parts, especially electronic components, of automotive vehicles have a limited storage life. Boissie *et al.* (2018) is researching a long term storage model to mitigate obsolescence at a car manufacturer.

The presented model of Boissie *et al.* (2018) has two goals. These are "to identify the possible storage durations for each part of a product, depending on the constituent materials and to calculate the cost of action to do, for each considered warehouse in order to make feasible a long-term storage" (Boissie *et al.*, 2018). The researcher identified that the storage life model is mainly based on the raw material used in the component. Therefore, components were classified according to their raw material. All raw materials were linked to adverse storage conditions, which can shorten the storage life. The risk factor of storing the raw material was additionally linked to the estimated storage time. Generally, suppliers recommend a maximum duration of 2 years without storage conditions. After two years, the storage is qualified as long-term. Storage from 2 to 5 years is considered as specific. If the storage life is estimated between 5 to 10 years, it is considered as risky. Beyond 10 years, the long-term storage is critical. "The result is a storage feasibility mapping model and an appropriate formulation for optimizing warehouse compliance operations" (Boissie *et al.*, 2018).

The researchers applied the presented model in a real automotive case study by analysing a "Jack Knife Key Case". The case is an assembly of 17 parts, which can be grouped into 8 raw materials. The final model matrix included the factors' raw material, estimated storage time, maximal storage time and storage condition. The result showed that three 3 out of 20 storage conditions met the requirements for storage time (Boissie *et al.*, 2018).

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Not only the development of new electric components automotive vehicles is changing the circumstances of the after-market. Presently a transformation from the conventional, individual kind of mobility, which was primarily operated by internal combustion engines, to a change of technology, driven by sustainable drive systems such as electric mobility, takes place. There is a general agreement that the change of mobility will have strong impacts on the entire supply chain" (Dombrowski and Engel, 2014).

Dombrowski and Engel (2014) conducted research which analyses the impact of electro mobility on the after sales service in the automotive industry. The research states that the future changes will have a negative impact on the after-market. The following five negative developments were identified (Dombrowski and Engel, 2014):

- Decreasing share of mechanical and moving parts
- Longer service intervals
- Immature battery technology
- Less additional units
- Limited self-service possibility

The mentioned developments are seen to worsen the situation of especially independent small and medium size garages, who will have to invest in equipment for services on electric cars of a variety of different brands. Furthermore, the research contains "the description of the development of a method which allows the after-sales service stakeholders to assess and adjust their existing after-sales service strategies" (Dombrowski and Engel, 2014).

c. Spare part production

Inderfurth and Kleber (2013) in cooperation with the Volkswagen AG are researching the spare part procurement for cars after the end of production. Three production strategies used in the automotive industry were identified. The traditional way of spare part acquisition is to place a large order for spare parts at the end of the serial car production. This strategy includes major stock holding costs and a high risk of obsolescence. The researchers estimate that 20% of Volkswagen's inventory of spare parts comes from final orders (Inderfurth and Kleber, 2013).

The extra production of spare parts and the remanufacturing of used parts is offering more flexibility in the procurement process. The extra production is usually done in internal facilities or external companies. The extra production can be controlled according to demand, but the production costs are

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much higher in comparison with the large order at the end of production due to the loss of economies of scale (Inderfurth and Kleber, 2013).

Remanufacturing is the recovery of used parts and is a further option for spare part acquisition. Remanufacturing causes moderate variable cost, but a reduced sale price in comparison to a new spare part shrinks the profit margin. Volkswagen's spare part inventory consists of only 2.5% remanufactured parts, which include high cost and vital parts, like engines and gearboxes (Inderfurth and Kleber, 2013).

Inderfurth and Kleber (2013) further developed a stochastic dynamic model for the spare part procurement including the three presented production strategies. The spare part supply period analysed is 15 years long, starting at the end of production of the serial production and ends at the end of service. The model shows that the optimum combination between the three options is difficult to find. Especially the final order must be made without experience in an environment of high uncertainty and dynamics of demand. In addition to this, the production strategies, extra production and remanufacturing, must be considered. The researchers claim that their model for optimum final order will decrease the performance lost on average by 50%. An additional 11% decrease in performance loss can be gained by implementing extra production and remanufacturing (Inderfurth and Kleber, 2013).

Dombrowski and Schulze (2008) describe six different options for the spare part procurement. During the service supply time of a series, the car manufacturers can combine different options to a strategy (Figure 2.22). Option number one is the utilisation of parts from the current series for spare parts of a complete series. This option is cost effective and a reliable supply chain. The disadvantage is the increased development effort that arises from considering the requirements of the old devices when developing new ones (Dombrowski and Schulze, 2008).
The spare part procurement options 2,3 and 4 are similar to Inderfurth and Kleber (2013), which were already presented and need no further explanation. The remanufacturing of parts outlined in Inderfurth and Kleber (2013) is split into two different aspects in Dombrowski and Schulze (2008). Firstly, reconditioning is the repair of assemblies with new spare parts. Secondly, used part recycling is the utilisation of used parts without repairs required. Both options are limited to parts which are repairable or recyclable and available. In addition to this, the remanufacturing must be economical and verifiable (Dombrowski and Schulze, 2008).

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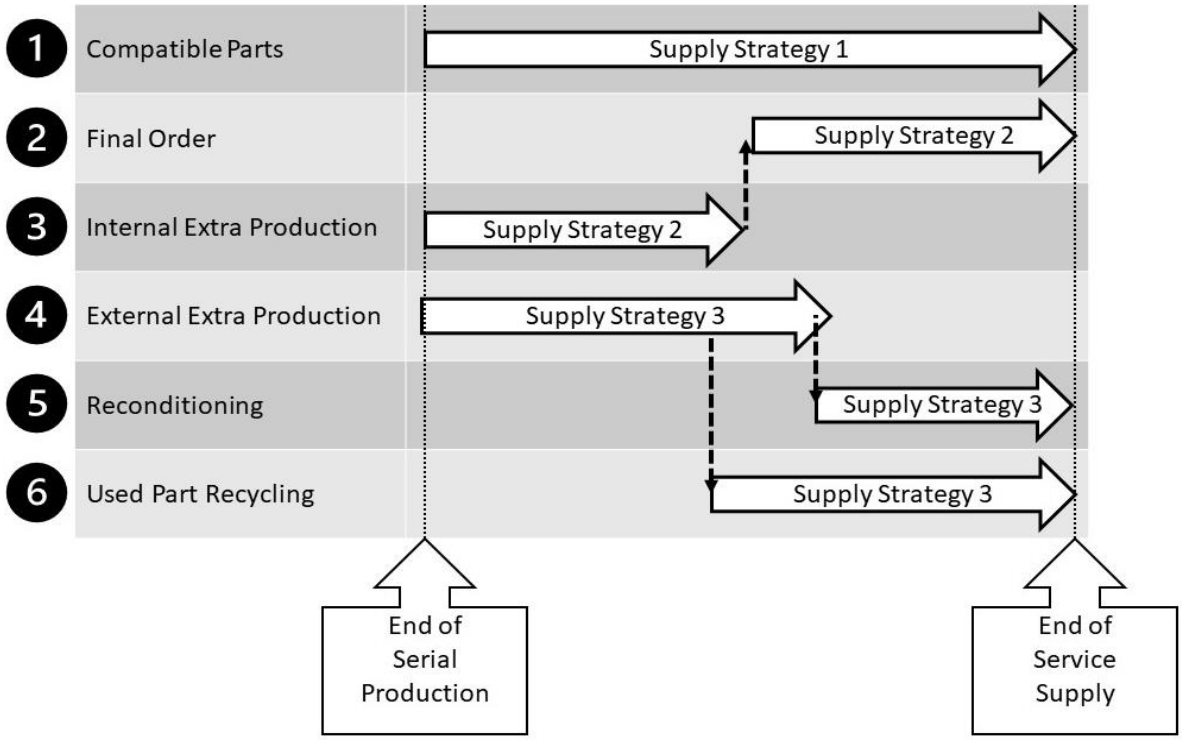

Figure 2.22: Combinations of supply strategies for different supply scenarios, adapted from Dombrowski and Schulze (2008)

As shown in Figure 2.22, different options can be combined to spare part supply strategies. While Supply Strategy 1 is a single option strategy, Supply Strategy 2 is combining the Internal Extra Production with the following Final Order. Supply Strategy 3 is relying on multiple options due to the issues and unpredictability of remanufacturing (Dombrowski and Schulze, 2008).

The textbook of Klug (2010) is another literature analysing the strategies for the spare part supply for automotive series which are out of production. After the end of the series, the basic decision must first be made for how long the spare parts will be supplied. For this purpose, demand forecasts are created which, depending on various parameters, decide the optimal strategy for post series supply. Klug (2010) presents four different strategies for the procurement of spare parts which can be used individually or as a combination:

- Continuous post-serial production
- Long-term storage
- Reconditioning
- Used part recycling

In general, after series production has been discontinued, spare parts are obtained from the series supplier. The series supplier usually moves the machines of the series production to a different

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location to manufacture spare parts for the after-market. Decreasing batch sizes lead to rising unit costs while the fixed set-up costs remain the same. The lower the number of items, the more uneconomical the process of continuous post-series production becomes due to the rising part prices. If the continuous post-series production becomes uneconomic, the car manufacturer places a final order for long-term storage. In the case of long-term storage, a quantity is ordered that is intended to cover the period until the end of service. "In the course of reconditioning, old parts are brought back from the market in order to recondition them in an industrial process and to sell them as replacement parts" (Klug, 2010). The keys for a successful reconditioning strategy are a functional recirculation system of used parts, a sufficient level of stock and a cost-efficient reconditioning and transport system. The recycling of used parts is, in contrast to the reconditioning, a process without industrial repair. This strategy is used, for example, for older vehicles when the prices of new parts are so high that they are not in a reasonable relationship to the value of the vehicle.

"Automotive remanufacturing is of growing importance within the automobile industry. Nowadays every OEM (original equipment manufacturer) has programs with remanufactured parts and their market volume is growing" (Casper and Sundin, 2018). However, the field of remanufacturing is also facing a wide range of challenges. The research of Casper and Sundin (2018) addresses these challenges. The following review will give an overview of the challenges discussed in their research report (Casper and Sundin, 2018):

- The sourcing of used parts and cores is influenced by vague taxation and transport regulations. The status of cores and the condition of used parts influences the level of tax. In addition, used parts are often contaminated with materials and fluids, which requires special safety regulation when transported.
- Three technical trends were identified which have an influence on remanufacturing. Firstly, products last longer due to better quality of material and production techniques. Secondly, more electronic components are assembled in modern cars. Many traditional remanufacturing companies have no sufficient knowledge and equipment in this field. Thirdly, the number of products in serial production which are not suitable for remanufacturing are increasing.
- The batches of used parts suitable for remanufacturing are too small for large car manufacturers to implement a serial remanufacturing process.
- The handling of a variety of parts results in complexity of processes. Furthermore, every used part comes in a different condition which includes uncertainty.

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Casper and Sundin (2018) claim that remanufacturing companies who are investing in staff, knowledge and machines, will profit from an attractive and growing industry (Casper and Sundin, 2018).

Guidat *et al.* (2015) carried out research giving insight to the state of the art of remanufacturing in Europe and investigating the impact of collaborations between companies on the profitability of remanufacturing. Although remanufacturing in general is not yet fully accepted in Europe, the car industry with its very high intensity of Aftermarket and Original Equipment sales is the exception. The processes in remanufacturing can be split into internal and external remanufacturing processes. Internal processes are all work floor activities like cleaning and disassembling. External processes are mainly logistics activities before and after the internal remanufacturing processes. This process chain usually includes more than one company (Guidat *et al.*, 2015).

Guidat *et al.* (2015) identified several barriers which can be summarised in three. First, the collection and reserve logistics which also includes the testing of cores before transportation. The management of the supply chain with worldwide transports and inventories is challenging. Second, the remanufacturing operations are facing high cost and complexity. The standardisation of processes like core testing, disassembly and cleaning is difficult with a large variety of products. Third, customers are uncertain about the quality and the poor structure of sales channels result in low and unstable market demand. Although several barriers were identified, economic and ecological reasons motivate companies to perform remanufacturing (Guidat *et al.*, 2015).

A survey conducted in the research of Guidat *et al.* (2015) shows that 82 % of remanufacturing processes surveyed, were initialized by the Original Equipment Manufacturer (OEM). The most important motivating factors for OEMs were profitability or growth, or existing demand. Further, the study indicates that an implementation of a remanufacturing network could improve the "production flexibility, lower risks, and better economies of speed and scale" (Guidat *et al.*, 2015).

The article of Ikeda (2017) reviews the history of remanufacturing of automotive parts in Japan and analyses possible measures to improve the competitiveness of remanufacturing. Since 2000, the Japanese government has enacted and amended several regulations and laws related to remanufacturing because of environmental aspects. Since then, "some car manufacturers added remanufactured parts to their aftermarket service program to extend their environmental activities" (Ikeda, 2017).

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Ikeda (2017) argues that automotive spare parts are most often required because of a vehicle breakdown. In this situation, customers do not consider environmental aspects which would benefit the sales of remanufactured parts. Instead, all spare parts must compete according to market factors like delivery time, price, quality and service. To compete in terms of price, the remanufacturing production processes need to be efficient, especially in the high labour cost country Japan. In addition, a core sourcing system is required to ensure a continuous supply of cores (Ikeda, 2017).

Conclusion

The aim of the scoping review of the spare part management of classic cars was to find information in literature which can help answer the research question of this subsection of literature review and to set a foundation of knowledge for further research. Although literature addressing the spare part management of classic cars was searched for, none of the e-Databases contained any documents covering this topic. Therefore, literature addressing the spare part management of the automotive industry in general was analysed to draw conclusions on the spare part management of classic cars.

Firstly, literature regarding the spare part classification was analysed. Various classifications models were presented. The most basic classification is the grouping into wear and faulty parts, while wear parts need replacement either because the service time exceeded, or the wear limit is reached. A further itemisation can be done with an ABC-XYZ-Analysis utilizing various parameters. This classification of automotive spare parts can also be applied to classic cars as well, since many components functionality remained the same throughout the years

Secondly, the supply chain performance measurement system of Chan (2003) was utilized to provide a structure for the analysis of the spare part management in the automotive industry. Table 2.6 shows the information gathered from the literature review integrated into the supply chain performance measurement system.

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Table 2.6: Summary of the supply chain performance in the spare part management of the automotive industry

	Sub level 1	*Sub level 2*	*Input from literature*
A. Quantitative	Cost	Distribution	• 2 Distribution channels (**DC**): Independent (**DC1**) and Dependent (**DC2**) aftermarket • Each channel consists (most often) of four parties: Producer, Wholesaler, Reseller, Workshops
		Manufacturing & warehouse	• 3 Supply Strategies (**SS**): ➢ **SS1**. Compatible production ➢ **SS2**. Extra production + final order ➢ **SS3**. Extra production + remanufacturing
	Resource utilisation	Labour, machine, energy	• Resource Utilisation differs throughout the supply strategies: ➢ **SS1**: Utilisation of efficient serial production ➢ **SS2**: Medium efficient extra production + uneconomic long-term storage ➢ **SS3**: Medium efficient extra production + labour intensive remanufacturing, but environment friendly
B. Qualitative	Quality	Customer dissatisfaction, customers response time	• No information from literature
		Stockout probability	• Risk of obsolescence: ➢ **SS1**: No obsolescence risk: continuous production ➢ **SS2**: High obsolescence risk: long-term storage ➢ **SS3**: Medium obsolescence risk: remanufacturing on demand, but obsolescence risk on remanufacturing spare parts
		Accuracy	• Dimensional accuracy and product quality might differ between the distribution channels (DC1, DC2) and supply strategies (SS1, SS2, SS3), due to different raw materials and manufacturing methods
	Flexibility	Output volume, output variety	• Output volume and variety depended on supply strategies (SS):

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			➢ **SS1**: High volume, low variety; dependent on serial production processes ➢ **SS2**: Low volume, medium variety; dependent on serial production machines, but independent from serial production processes ➢ **SS3**: Low volume, high variety; remanufacturing is manual work and allows variety
		Modifications, integrating of new products	• Modification and new products depended on supply strategy (SS): ➢ **SS1**: No modifications due to series production processes, good integration of new products ➢ **SS2**: Extra production allows modifications, integration depended on the storage capabilities ➢ **SS3**: Extra production allows modifications, remanufacturing allows modifications, integration of new product requires adjustments in the remanufacturing process
	Visibility	Time, accuracy	• Most spare parts have a delivery time of 24 hours, with a service level of 98%
	Trust	Consistency	• Spare part delivery obligations are often extended to a certain point by the car manufacturers
	Innovativeness	Launch of new products	• Higher potential of new product launches in the independent distribution channel (DC 1), due to more flexible processes compared to the depended distribution channel (DC2)
		Use of new technology	• Use of new technology is depended on the supply strategy (SS): ➢ **SS1**: Technology of the latest series is used ➢ **SS2**: Use of new technology possible until long-term storage ➢ **SS3**: Use of new technology possible

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The charting of the data from literature using the supply chain performance measurement model (Table 2.6) shows that most measure units are addressed. Two distribution channels were identified which can use three different supply strategies. This information is relevant for classic cars since these circumstances are not changing when considering classic cars. Especially the measures "Stockout probability" and "Output volume and variety" are relevant for classic cars since the risk of obsolescence is dominant and low volume production is required for rare classic cars. The Sub-level-2 category "Customer Dissatisfaction, Customers Response time" was the only issue not mentioned in the literature. The measures which fall under the category "Innovativeness" show which distribution channel and supply strategy may include a new technology like additive manufacturing better.

2.5 Additive manufacturing for spare parts in the automotive aftermarket

2.5.1 Introduction

"Production and management of spare parts are among the most promising applications of additive manufacturing, and these additive manufacturing applications are progressively being adopted across different industrial domains" (Heinen and Hoberg, 2019). Additive manufacturing has the potential to make components directly from digital files instead of high-cost fixed asset processes like moulding. Further, researchers state that additive manufacturing enables production on demand closer to the customer's location. Therefore, additive manufacturing is associated with supply chain performance improvements (Eggenberger, Oettmeier and Hofmann, 2018; Reeves and Mendis, 2015).

2.5.2 Supply chain management framework

The supply chain performance measurement model of Chan (2003), presented in Chapter 2.4.2, will be utilized to develop the literature research questions for this scoping review. The model was also used to conclude the performance of the spare part supply chain utilizing additive manufacturing. Furthermore, analysing the current supply chain and the supply chain using additive manufacturing in the same model, enabled a direct comparison

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2.5.3 Literature review – additive manufacturing of automotive parts

The literature scoping review on the subsection "Additive manufacturing for spare parts in the automotive aftermarket" covered two main topics. Firstly, literature was found regarding the production of parts for the automotive serial production, which was presumed to provide information about the feasibility to use additive manufacturing to produce spare parts as well. Secondly, literature was found which analyses the impact of additive manufacturing on the spare part management of spare parts in the automotive industry. In the following, the five-step process of the scoping literature review was conducted.

Step 1: Identifying the research questions

The goal of this literature review is to identify literature which contains information on how to integrate additive manufacturing into the spare part management of classic cars. Furthermore, the impact of additive manufacturing on the current spare part management of classic cars should be addressed. Therefore, the following research questions are based on the research objectives, the information from the previous literature reviews and the supply chain performance measurement model:

Reserch Question 1	How does the process chain configuration of spare part manufacturing change when utilizing additive manufacturing?
Reserch Question 2	Which spare parts are suitable for additive manufacturing?
Reserch Question 3	Which influence does AM have on the performance of the supply chain of spare parts for classic cars?
Reserch Question 4	Which criteria influence the success of AM for the production of classic car spare parts?

Step 2: Identify relevant studies

As in the first two literature reviews in Chapter 2.3.3 and Chapter 2.4.3, the scoping review framework of Arksey and O'Malley (2005) was utilized. Basic exclusion criteria based on the date of publication were given due to the fast development of additive manufacturing. Therefore, literature with a date of publication of 2014 or older were excluded from the scoping review. All sources written in English and German were considered. The final search strategy included the e-Databases Wiley, Science Direct and Springer Link. Furthermore, the e-Databases were accessed through the

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membership of “University of Stellenbosch” and “Hochschule München” to expand the accessible literature.

The search for literature was executed using the following search string in English:

- “Additive manufacturing” OR “3d printing” OR “rapid manufacturing” OR “binder” OR “printing” AND “spare part” OR “after-market” OR “production” OR “part” OR “component” OR “design” OR “research” OR “development” OR “serial” AND “car” OR “automotive” OR “vehicles” OR “classic car” OR “vintage car” OR “truck”

The corresponding search string in German:

- “3D-Druck” OR “Additive manufacturing” OR “Rapid manufacturing” OR “Binder” OR “Jetting” AND “Ersatzteil” OR “Reperatur” OR “Teil” OR “Komponente” OR “Forschung” OR “Entwicklung” OR “Design” AND “Automobil” OR “Fahrzeug” OR “Oldtimer” OR “Kraftfahrzeug”

Step 3: Select studies and statistics

Publications addressing issues of additive manufacturing in the automotive industry were considered if they included the manufacturing of serial parts or spare parts. Publications which were addressing, for example, the prototyping, tooling, or the production of casting moulds with additive manufacturing, were not considered. Furthermore, other automotive industries, like the aviation or ship industry, were not considered.

The PRISMA-ScR flow diagram was used as a template to illustrate the record selection process for the review (Figure 2.23). In the Identification phase, 30 records were found in the three electronical databases. The title and abstracts of these records were screened in phase two. In this phase, 18 records were excluded because their content did not suit the research questions of this literature review. The resulting 12 records were assessed, in the third phase, in a full-text analysis to identify whether the content is contributing towards a base of knowledge, or whether the record has to be excluded. In the last phase, the remaining eight records were analysed for the inclusion in this scoping literature review.

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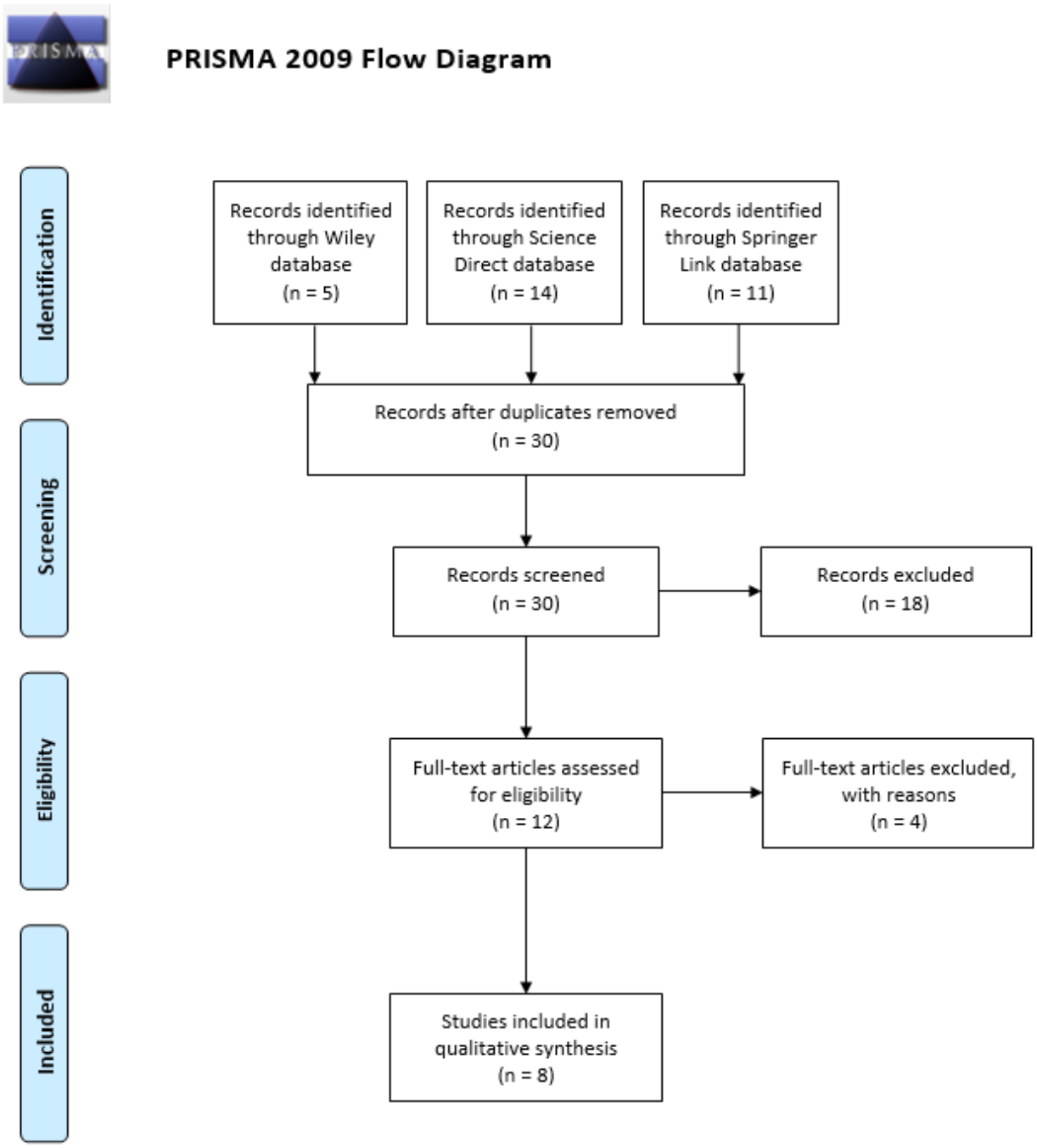

Figure 2.23: PRISMA-ScR Flow Diagram for the literature review of additive manufacturing for spare parts in the automotive aftermarket, adapted from Rouse (2016)

Step 4: Chart the data

Of all studies identified as relevant, the data and information will be extracted. The documents were categorized as listed using the qualitative data analysis software "ATLAS.ti". The analysis of the records according to its characteristic and content led to coding groups and codes as listed in Table 2.7.

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Table 2.7: Categories for the analysis of literature regarding additive manufacturing for the spare part in the automotive aftermarket

Coding groups	*Codes*
Paper characteristics	• Title • Year of publication • Location of publication • Publication database • Publication type
Component manufacturing	• Process • Materials • Design optimisation • Environment
Spare part supply chain	• Layout • Performance

The charting of the literature according to the year of publication indicates that additive manufacturing in the automotive industry received a slightly increased attention in the 2019 and 2020. Figure 2.24 shows that the majority of the selected literature were published in these two years.

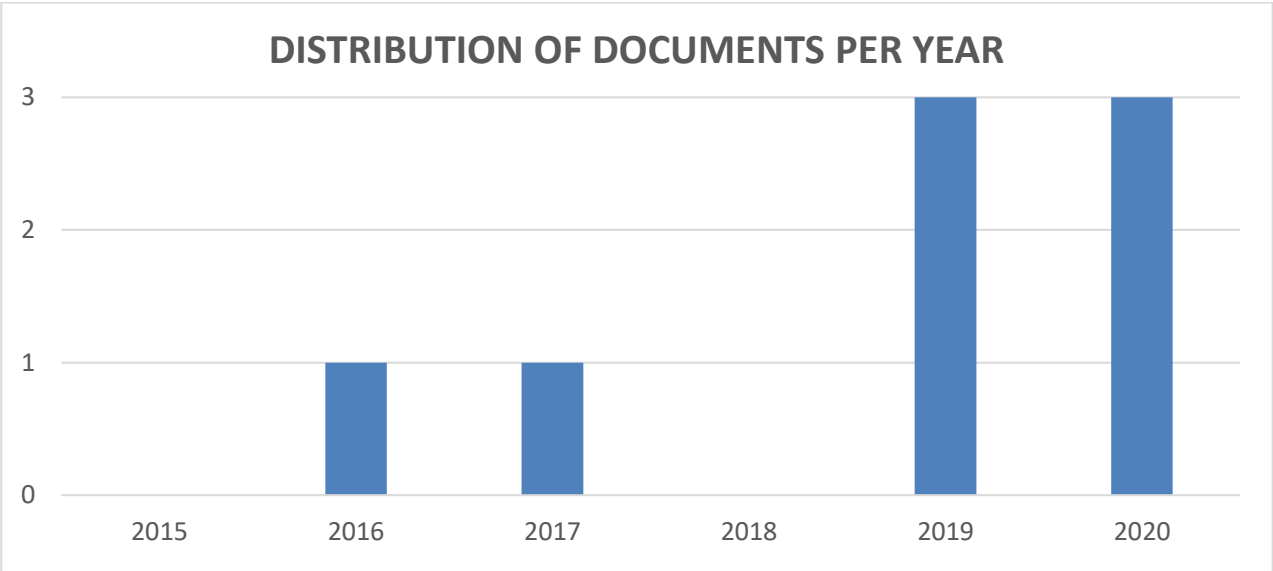

Figure 2.24: Distribution of documents per year for the literature review of additive manufacturing for spare parts in the automotive aftermarket

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All literature found for the scoping literature review were coded according to the type of publication and the source of the document. Figure 2.25 shows that half of the literature was published as a journal article. Three conference papers and one general article complete the pie chart. Figure 2.25 charts the source of the documents found. Five documents were sourced from Science Direct and three from Springer Link. None of the documents found through the Wiley database were included into the literature scoping review.

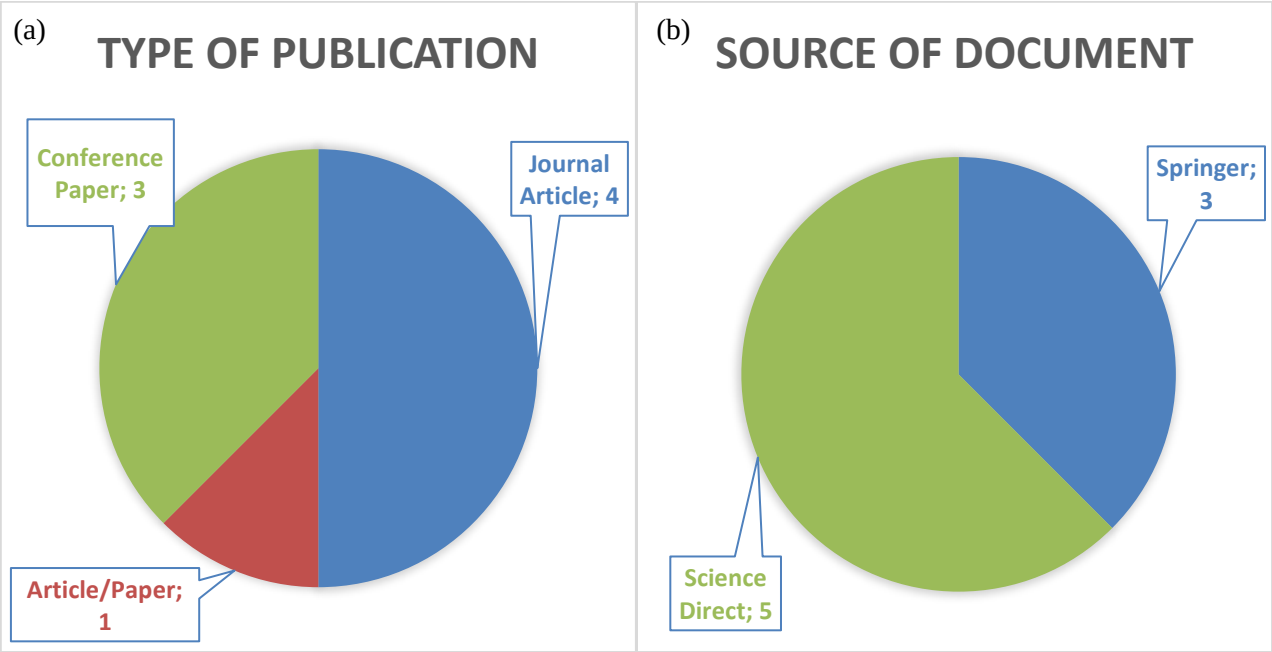

Figure 2.25(a) and (b): (a) Type of publication of the documents found for the literature review of additive manufacturing for spare parts in the automotive aftermarket; (b) Sources of the documents found for the literature review of additive manufacturing for spare parts in the automotive aftermarket

Furthermore, the location where the documents had been published was coded for further analysis. Figure 2.26 shows that research on this topic was conducted in countries which are known for car manufacturing, like Germany, Italy, and Sweden. However, research was also conducted in other countries which are not known for large car manufacturers, like Canada, Croatia, and Switzerland. Although the search included search strings in German, none of the entries were written in German.

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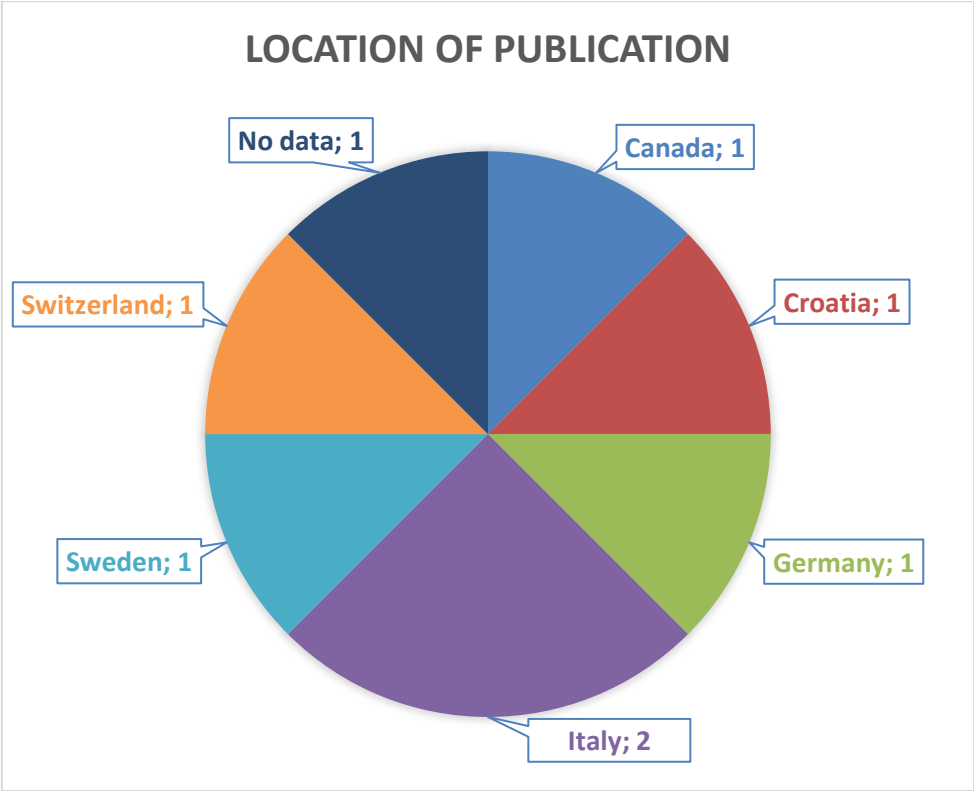

Figure 2.26: Location of publication of the documents found for literature review of additive manufacturing for spare parts in the automotive aftermarket

All entries resulting from the search strings could be grouped into three main areas shown in Table 2.8. One entry describes the actual state of additive manufacturing in the automotive industry. Four entries analyse parts of the additive manufacturing process and the impact on the environment. Lastly, three entries analyse the layout and performance of potential spare part supply chain models. In step 5, the themes of the records to each coding group is summarised.

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Table 2.8: Mapping of the documents according to their context in the literature review of additive manufacturing for spare parts in the automotive aftermarket

Context	***Articles***
I. AM in the automotive industry	Nichols (2019);
a. Component manufacturing	Bacciaglia, Ceruti and Liverani (2020); Böckin and Tillman (2019); Jankovics and Barari (2019); Wiese, Thiede and Herrmann (2020);
b. Spare part supply chain	Eggenberger, Oettmeier and Hofmann (2018); Delic and Eyers (2020); Savastano *et al.* (2016);

Step 5: Collate, summarise, and report the results

I. Additive manufacturing in the automotive industry

Additive manufacturing has passed the development status of being a home application for hobbyists. The car manufacturing industry has identified additive manufacturing as a way of manufacturing which can make "commercial and personal vehicles more affordable and available than ever before" (Nichols, 2019). Nichols (2019) is giving an overview of the benefits of 3D metal printing for the automotive industry. The researcher has identified 4 promising applications for now and in the future:

- Prototyping: In every development phase of a new series, small scale models and prototypes are being built. 3D metal printing can be used to create those models, functional car prototypes, rapid manufactures tools and replacement parts.
- Rare spare parts: If a rare spare part runs out of stock, special tooling is often required for the extra production of those parts. Additive manufacturing does not require tooling and is therefore a cost-effective alternative for the manufacturing process. In addition, stock can be reduced, because parts can be printed to order.
- Bespoke car design: The customization possibilities on cars at the car manufacturers is often limited to colour options and add-ons. 3D metal printing gives the opportunity for car manufacturers to offer their customer individualization on for example the body work or interior appearance surfaces.

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- Lightweight constructions: Lighter vehicles also use less fuel, increasing fuel economy and reducing the amount of carbon dioxide and monoxide. By using 3D metal printing with the opportunity of creating latticed parts weight reductions by up to 80% can be achieved.

The aim of car manufacturing is to build a car where most parts are printed. Nowadays, producing the main features of a car with 3D printers is possible, but conventional production techniques are still faster and more efficient (Nichols, 2019).

a. Component manufacturing

"The Reverse Engineering acronym is used to describe the bunch of techniques used to obtain the digital 3D model of a component" (Bacciaglia, Ceruti and Liverani, 2020). Reverse engineering is used, if the physical part is available and a 3D model is created to understand how the components work, what its geometrical shape is and how it is used. Bacciaglia, Ceruti and Liverani (2020) are reviewing the reverse engineering technique of photogrammetry for the spare part production in the automotive industry utilizing additive manufacturing (Bacciaglia, Ceruti and Liverani, 2020).

The principle of photogrammetry is to create a 3D model by applying a remanufacturing algorithm on a series of pictures taken from the physical part. Necessary for the photogrammetry process are a high-resolution camera, for example, a smartphone and a software tool, which makes this technique affordable. Therefore, a decentralized scanning and additive manufacturing process is a feasible economic scenario (Bacciaglia, Ceruti and Liverani, 2020).

In a single case study, the researchers Bacciaglia, Ceruti and Liverani (2020) selected an automotive component to evaluate the feasibility and the precision of state-of-the-art technique. Figure 2.27a shows the first step of the reverse manufacturing process. The selected part, an engine sump, is captured from multiple angles with a digital camera. The photos were imported into the Autodesk Recap Photo tool (Figure 2.27b), and afterwards imported to Zephyr 3DF (Figure 2.27c) to increase the accuracy of the results.

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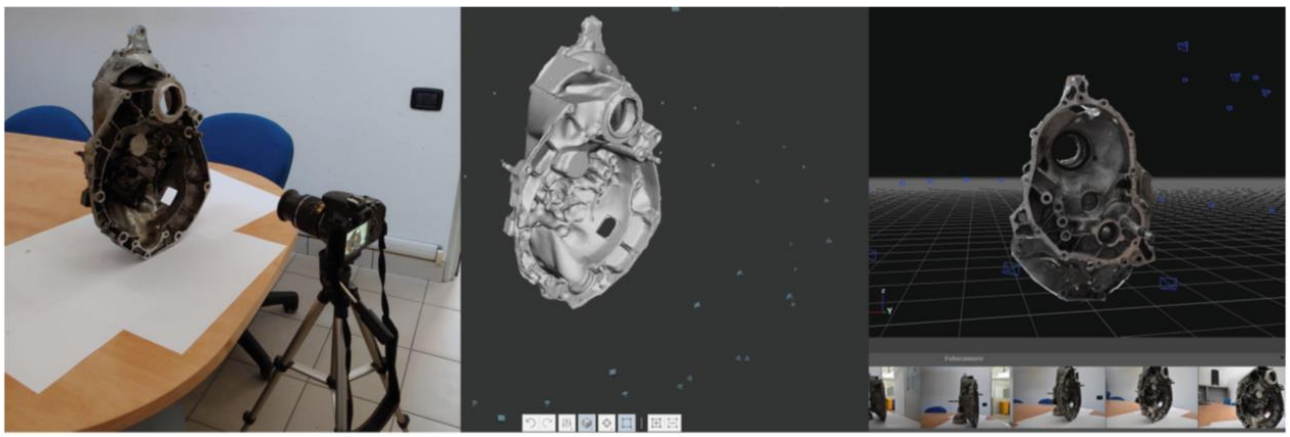

a b c

Figure 2.27 (a), (b) and (c): (a) Real component geometry is captured using a digital camera; (b) dense cloud point in Autodesk Recap Photo; (c) dense cloud point in Zephyr 3DF, sourced from Bacciaglia, Ceruti and Liverani (2020)

A surface mesh was obtained in a scaling operation in process step 4 (Figure 2.28a). In Figure 2.28b the part was imported to MethLab to smoothen and fix the mesh. In Figure 2.28c the STL file was created and imported to the additive manufacturing machine to evaluate the feasibility.

a b c

Figure 2.28 (a), (b) and (c): (a) Scaling the component by a known dimension; (b) surface mesh smoothing in MeshLab; (c) STL file imported in CURA ready to be 3D printed, sourced from Bacciaglia, Ceruti and Liverani (2020)

Performing this case study showed "a maximum error of 1.133 mm is noticed (1.86%) in the 3D digital model with respect to the real part in a region selected for benchmarking tests" (Bacciaglia, Ceruti and Liverani, 2020). This result leads the researchers to the conclusion that with today's photogrammetry technology large errors are noticed. Therefore, human intervention is required to fix the part model by adding precise dimensions for couplings and interferences. "Future advances in digital equipment, software tools and hardware computational power will probably reduce the errors in 3D reconstruction, making it useful for a wide number of parts" (Bacciaglia, Ceruti and Liverani, 2020).

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Before the process steps of printing the part with additive manufacturing machines, the design of parts can be adjusted to suit additive manufacturing. “Additive manufacturing enables the straightforward creation of complex structures that otherwise would require many processing steps, or not be feasible at all” (Jankovics and Barari, 2019). The research of Jankovics and Barari (2019) is addressing the customisation of automotive structural components using additive manufacturing and topology optimization. “Topology optimization refers to a form of structural optimization that is designed to find an optimal geometry based on a set of constraints” (Jankovics and Barari, 2019). Finding the optimal geometry of a component can result in inherent weight-savings. Weight-savings in the automotive industry lead to improvements in fuel economy, which helps automotive manufacturers to meet their targets regarding environmental regulations (Jankovics and Barari, 2019). The use of topology optimization in combination with additive manufacturing for automotive components is influenced by 3 major issues:

- Topology Optimization Method
- Additive Manufacturing Overhang Constraints
- Build Time Constraints

“One of the most widely used topology optimization methods is known as the solid isotropic material penalization scheme” (Jankovics and Barari, 2019). The objective is to maximize stiffness while satisfying a constraint such as volume or mass. The optimal solution of maximum stiffness under the given constraints is the result of various iterations. The visualization of one mathematical iteration process example is shown in Figure 2.29.

Figure 2.29: Topology Optimization with design domain and boundary condition on the left, with various iteration results shown, sourced from Jankovics and Barari (2019)

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Due to the nature of layer-based additive manufacturing, there exists a limit to the amount of overhang to which material can reliably be deposited on. This is dependent on the angle of the wall of the part with respect to the build platform (Figure 2.30), with the exact limit often being approximately 45°.

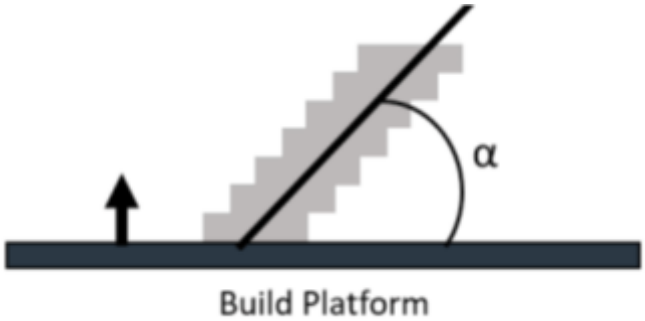

Figure 2.30: Maximum angle of layer-based processes, sourced from Jankovics and Barari (2019)

The basic idea of adding an overhang constraint into the topology optimization is "the penalization of material that violates the various angle constraints" (Jankovics and Barari, 2019). As with the constraint for build angle, the build time constraint can be added for reducing the amount of material to be printed. The build time in an additive manufacturing process can be measured by the amount of material per layer of the model to be printed. To reduce the amount of material per layer, the researcher suggests a penalty system, similar to the maximum build angle. The idea of that system is to shrink the exterior perimeter and exceed interior perimeter with the goal of collapsing any voids in the slice (Jankovics and Barari, 2019).

In a single case study, the researcher applied the presented topology optimization process on a part of the automobile industry. A wheel upright from a wheel assembly of a formula race car was selected because a lightweight design is critical in this automotive area and funds for developments are available. Figure 2.31 shows the wheel upright after the topology optimization. In addition to the overhang and build time constraints, the maximum dimensions inside the wheel rim and the boundary condition for maximum loads were considered in the development process. The researcher states, that "using a basic topology optimization scheme, the results show an organic shape that minimizes compliance, with a 78% reduction in mass from the design domain" (Jankovics and Barari, 2019).

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Figure 2.31: Topology optimisation of a wheel upright, sourced from Jankovics and Barari (2019)

"Additive manufacturing is moving towards series manufacturing applications across a variety of industries. However, take-up for series production in the automotive industry is still slow and limited to very few materials" (Wiese, Thiede and Herrmann, 2020). The research of Wiese, Thiede and Herrmann (2020) is addressing the limitation of polymer additive manufacturing regarding materials and processes in the automotive industry. The research report is providing an overview of previous research conducted and introduces a material and process selection method based on the automotive industry standards (Wiese, Thiede and Herrmann, 2020).

The production of end-use parts with additive manufacturing methods directly from CAD models is called rapid manufacturing. Rapid manufacturing was forecasted to have a high impact on product manufacturing, but it could not meet this expectation yet. The researcher names process limitations, material availability and knowledge barriers as the main reasons for this restrained development. However, applications of rapid manufacturing for parts of the automotive industry are recognised. The examples found by the researcher were aftermarket and small series trims, window guide rails, brake brackets, air vents and cable routing covers. The driving forces for the adoption of additive manufacturing were in 5 out of the 6 applications, the small number of parts. Only the aftermarket trims driving force was the possibility for customisation (Wiese, Thiede and Herrmann, 2020).
Furthermore, the analysis of previous research reveals 4 findings, which are related to materials and processes of additive manufacturing for serial parts of the automotive industry:

- Additive manufacturing parts can show inferior properties, heavily depending on the utilized process and base material.
- Composite materials can mitigate inferior properties by offering a comparably better material performance.
- Processing of materials highly depends on machine layouts and therefore processability of materials differs depending on process and material combination.

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- The spectrum of materials for polymer additive manufacturing processes is limited and may inhibit development of applications.

To address and discuss the 4 findings, Wiese, Thiede and Herrmann (2020) set up a material and process selection method. The method is designed for an evaluation of additive manufacturing early in the automotive product development process. The result of applying this method is an index to rate compatibility of materials across various processes. Not every available machine can process every material in its additive manufacturing process. Thus, apart from selecting appropriate materials solely according to mechanical and thermal properties, the restrictions in material-machine compatibility must be considered.

A high compatibility of a material-process combination is achieved if it meets the requirements of the automotive industry. The requirements are based on the VDA 232-201 standard of the automotive industry and can be grouped by the following (Wiese, Thiede and Herrmann, 2020):

- Mechanical requirements
- Thermal requirements

VDA 232-201 lists relevant parameters and testing methods for multiple mechanical properties that apply to material data sheets for additive manufacturing materials, for example, tensile modulus, yield strength or Charpy impact strength. “Mechanical requirements for automotive applications heavily depend on the area where the final part is installed” (Wiese, Thiede and Herrmann, 2020).

The thermal requirements are based on multiple criteria as well, for example, the melting point, heat deflection temperature or Vicat softening temperature. “Temperatures can rise to substantial levels in the vehicle interior. Surfaces exposed to direct sunlight like dashboards, trunk covers, or upper door panels heat up to high temperatures due to combined effects of solar radiation and ambient temperatures” (Wiese, Thiede and Herrmann, 2020). Figure 2.32 indicates the surface maximum temperatures of vehicles in use on areas which are in general manufactured out of polymer materials.

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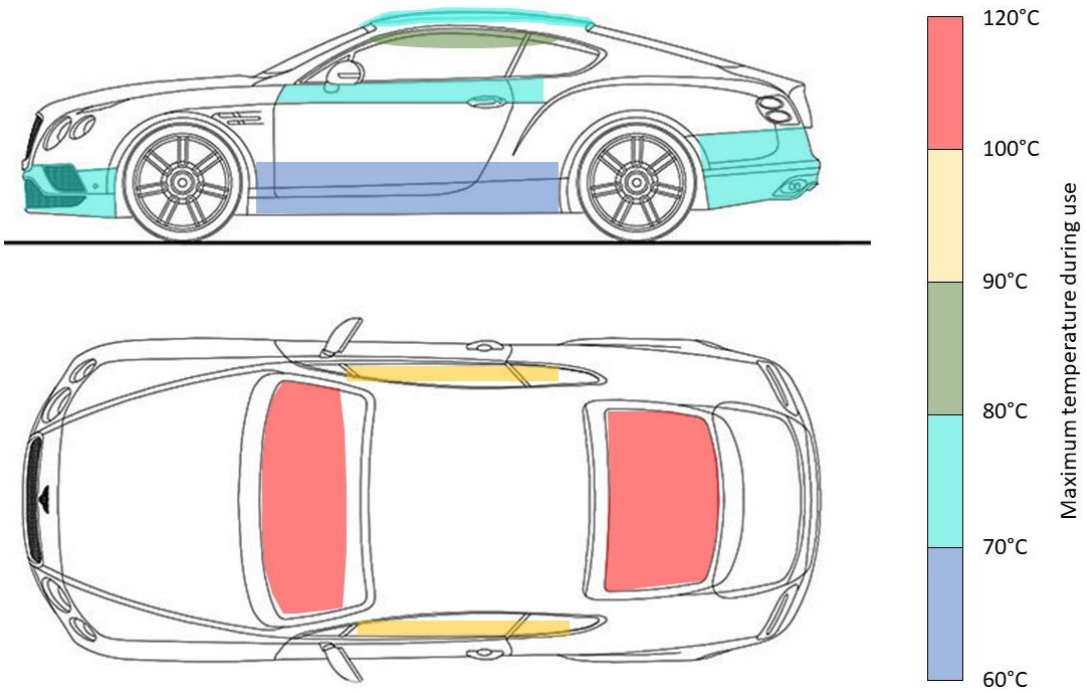

Figure 2.32: Expected maximum temperature ranges during vehicle service, adapted from Wiese, Thiede and Herrmann (2020)

Figure 2.33 visualises the relations between all processing machines and materials that have been evaluated in this reviewed research. The figure indicates the level of compatibility of machines (row indices) with materials (column indices). "As an example, 91 % of SLS machines used for this analysis are able to process the material PA 12, resulting in a very high compatibility, while just 4% can process the high-performance material PEEK, indicating a very low compatibility" (Wiese, Thiede and Herrmann, 2020).

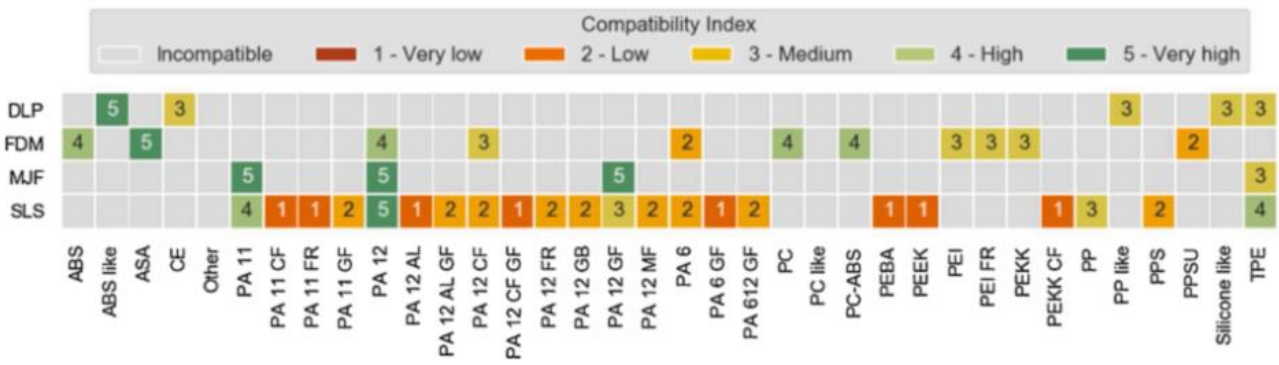

Figure 2.33: Compatibility index for selected AM process and material combinations, sourced from Wiese, Thiede and Herrmann (2020)

The presented material and process selection method applied on the automotive requirements from VDA 232-201 lead the researchers to the following conclusions (Wiese, Thiede and Herrmann, 2020):

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- Thermal requirements are a challenge for thermoset-based processes, as most materials are not temperature-resistant. Only thermoplastic processes offer more temperature resistant materials
- Two materials are promising to fulfil the mechanical requirements
- Composite materials can offer better mechanical and thermal properties but are mostly tailored to a few machines. These material-machine incompatibilities may be a high barrier for users due to high investments into systems with low material flexibility.
- Application development for automotive series parts is inhibited due to limited material portfolios. Polymers frequently used in automotive product development are barely available. These engineering thermoplastics are limited to powder bed fusion (PBF) and metal extrusion (ME).
- PBF processes prove most promising for manufacturing with high mechanical and thermal requirements.

Powder-based fusion was also the technology of choice in the research of Böckin and Tillman (2019). Their research investigates "the environmental and resource implications of additive manufacturing for automotive applications while searching for the most important factors influencing results" (Böckin and Tillman, 2019). In cooperation with the Volvo Group, the researchers compare conventional and additive manufacturing methods by applying them to the case of a light truck engine.

Additive manufacturing is prophesied to have an improved resource efficiency and environmental performance. These benefits can be achieved by a redesign of components specifically for additive manufacturing. For example, lightweight design can increase fuel efficiency or complex assemblies' designs can be simplified to reduce production resources. In addition, parts can be redesigned to improve its performance and efficiency, for example, by improved cooling. The aerospace industry provided evidence for additive manufacturing in high performance applications such as turbines, hydraulic valves and turbine nozzles (Böckin and Tillman, 2019).

In this case study, the life cycle assessment of a light truck engine is performed in certain system boundaries. Figure 2.34 shows the steps in the life cycle of the engine that are considered in this study. The process step of manufacturing a component can be conducted either with conventional or with additive manufacturing methods. According to that, the previous steps of raw material extraction and raw material processing can differ for each manufacturing method. The assembled engine is installed

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in the truck and consumes fuel while the truck is driving until it is scrapped at the end-of-life (Böckin and Tillman, 2019).

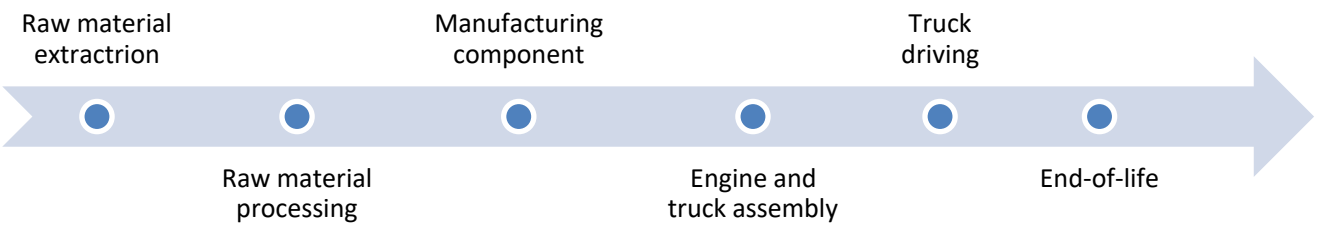

Figure 2.34: Simplified flowchart showing the life cycle of the engine mounted in a light distribution truck, as well as the system boundaries of the study, adapted from Böckin and Tillman (2019)

The life cycle analysis is performed under three different scenarios:

- Scenario 0 (S0): Conventional life cycle
- Scenario 1 (S1): Present state of additive manufacturing
- Scenario 2 (S2): Future state of additive manufacturing

S2 underlies the assumption that additive manufacturing, in particular powder bed fusion, will develop in the future. This includes that the process will be suitable to use low-alloy steel and printing larger engine components, which could increase the share of additive manufacturing components (from 20% share in S1 to 80% share in S2) in the engine assembly. Additive manufacturing is assumed to reduce the weight of a component on average by 25%. This weight reduction increases the maximum load capacity of the truck for transport goods at the same level of fuel consumption, resulting in better transport efficiency. However, the electricity consumption for manufacturing components in each scenario is considered as well. The resource consumption of shredding and melting of the engine at the end-of-life is dependent on the raw material used in the component manufacturing process (Böckin and Tillman, 2019).

The results of the environmental impact study show that the future scenario S2 has environmental improvements. The main reason for these improvements is the weight reduction and the resulting lower fuel consumption in use. For the present state of additive manufacturing S1, the study indicates that the implementation is not beneficial yet without technological development. However, this study of Böckin and Tillman (2019) was limited to available data of additive manufacturing processes. That means, that the results may change if the following issues would be implemented into the assessment:

- A reduction of fuel consumption of the engine by an increased efficiency due to additive manufacturing.

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- A reduction of electricity consumption for additive manufacturing processes could be achieved in future.
- Electricity is assumed to have a low share of fossil fuel in the future scenario (assumed for Sweden, the location of the researchers).
- A reduction of spare part handling and its environmental effects when producing spare parts on demand with additive manufacturing.

b. Spare part supply chain

Additive manufacturing as a disruptive manufacturing method has the potential to change the current supply chain of spare parts. Savastano *et al.* (2016) are researching the state of the art of additive manufacturing with a focus on the potential impact on the companies´ strategy for the management of spare parts. After an introduction of additive manufacturing, the researcher compares additive manufacturing with the conventional manufacturing methods and ends their research with an explorative study in the automotive industry (Savastano *et al.*, 2016).
"An important challenge is that companies need to support the previous generation of their products as well as their new products. This obligation amplifies the number of stock keeping units in after-sales inventories and relevant costs" (Savastano *et al.*, 2016). Additive manufacturing has the potential to create spare parts on demand to reduce cost and improve the supply chain dynamic (Savastano *et al.*, 2016). Although additive manufacturing has several advantages, the new technology must still compete with the conventional manufacturing methods. The researchers state that 4 main drivers made additive manufacturing possible to reach the level receiving attention of companies investing in the production technology:

- Rapid cost reduction: Equipment costs decreased, while technology improved.
- Increase in quality*:* Higher resolution with an increased strength and surface finish.
- Increase in variety of supported materials: Good adaptability of additive manufacturing machines to new materials.
- Expiration of critical patents: One additive manufacturing process patent expired, and other expirations will follow in the future.

For manufacturers and providers of spare parts, additive manufacturing shows several benefits compared to the conventional techniques. First, the redundancy of tooling enables customisation and design changes within a short implementation time. Further, complex geometries are feasible to print

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and small batch sizes are economical. Second, additive manufacturing has the potential to simplify supply chains, with shorter lead time and lower inventories. In addition to the benefits of the manufacturer, the customer of additive manufactured parts is enabled to customise the product according to personal needs. By implementing new retail models, the customer can be involved into the design process. In addition, the customer can be involved in the production process, by printing the part at home (Savastano *et al.*, 2016).

The research objective for Savastano *et al.* (2016) was "to explore possible positive correlations between the adoption of AM technologies in the Automotive industry and improved efficiency of the supply chain" (Savastano *et al.*, 2016). To provide evidence for the presented content so far, a case study with a spare part from the automotive industry was performed. The spare part was selected from a car that had to meet the following requirements in order to benefit from the from the advantages of additive manufacturing:

- City car
- Widespread on the market
- Out of production
- Characterized by a high percentage of plastic parts (internal/external)

To fully analyse the impact of additive manufacturing on the supply chain of spare parts in the automotive industry, the impact on the manufacturing and distribution channels were investigated by the researchers. Three different spare part provision scenarios were identified (Savastano *et al.*, 2016):

- The actual scenario (1)
- The distributed production scenario (2)
- The future outsourced scenario (3)

The actual scenario (1) is based on the supply chain configuration of the traditional centralized production. The part is produced at the headquarter of the part manufacturer and distributed via resellers to the consumer. This scenario is characterized by high cost for transport and storage of parts. In the distributed production scenario (2) distribution costs were estimated to not be relevant. The spare part is produced on demand in a decentralized additive manufacturing machine and distributed locally to the customer. Instead of distribution costs, depreciation costs of investments in machines have to be considered in this scenario. For the last scenario (3), car manufacturers could

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avoid building an individual decentralized production network, when the spare part provider utilises capacity of so-called "Printer Farms" of third-party suppliers to make products on demand (Savastano *et al.*, 2016).

Based on the findings of this study, the researchers conclude that additive manufacturing will not replace traditional manufacturing techniques, rather work in a hybrid solution. Companies utilizing this hybrid technology will have the opportunity to decide for every component if it can benefit from the characteristics of additive manufacturing. The benefits of cost reduction or improvement in performance are likely to be achieved with components which have "high labour-cost elements, complex tooling requirements, relatively low production volumes, high obsolescence or waste rate" (Savastano *et al.*, 2016).

The research of Eggenberger, Oettmeier and Hofmann (2018) is addressing a similar research question as the research of Savastano *et al.* (2016). Eggenberger, Oettmeier and Hofmann (2018) answer the question of the effects of additive manufacturing in automotive spare parts supply chains. The research report first provides background information about additive manufacturing and the spare part management in the automotive industry. Second, the implementation of additive manufacturing in the supply chain of spare parts in the automotive industry is analysed based on four supply chain scenarios. The similar research topic and research approach of Eggenberger, Oettmeier and Hofmann (2018) and Savastano *et al.* (2016) enables a close comparison of their results.

The automotive spare part management is a challenge for manufacturers to provide a high service level while keeping cost for spare parts low. The "current spare parts supply chains are characterized by high volume production, long transportation distances and capacious warehousing" (Eggenberger, Oettmeier and Hofmann, 2018). In this statement, both research groups are corresponding. In addition Eggenberger, Oettmeier and Hofmann (2018) state that the aftermarket generates about half of the profit of carmakers in the European Union, which indicates an enormous potential for revenue (Eggenberger, Oettmeier and Hofmann, 2018).

Further, Eggenberger, Oettmeier and Hofmann (2018) investigate different scenarios for the implementation of additive manufacturing into the supply chain of spare parts. The two research groups identified the same 4 supply chain scenarios:

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(1) Centralized additive manufacturing implementation (The actual scenario)
(2) Hybrid additive manufacturing implementation (Centralized scenario)
(3) Decentralized additive manufacturing implementation (The distributed production scenario)
(4) Outsourcing of additive manufacturing implementation (The future scenario)

The research of Eggenberger, Oettmeier and Hofmann (2018) discusses the 4 scenarios in more detail than the other group. Additional to previously mentioned information, this research report provides for all scenarios an illustration of the supply chain and propositions.

The centralized supply chain implementation (1) is the first one to be illuminated. This scenario is based on the actual supply chain of spare parts produced with conventional manufacturing methods. The supply chain is illustrated in Figure 2.35. Three different types of arrows highlight the flow material, information, and finances. The raw material for the additive manufacturing process at the original equipment manufacturer (OEM) is provided from the raw material supplier. The finished part is distributed and stocked at the regional distribution centre (RDC) and at the part distribution centre (PDC). Last, the part is delivered to the dealer and installed for the customer.

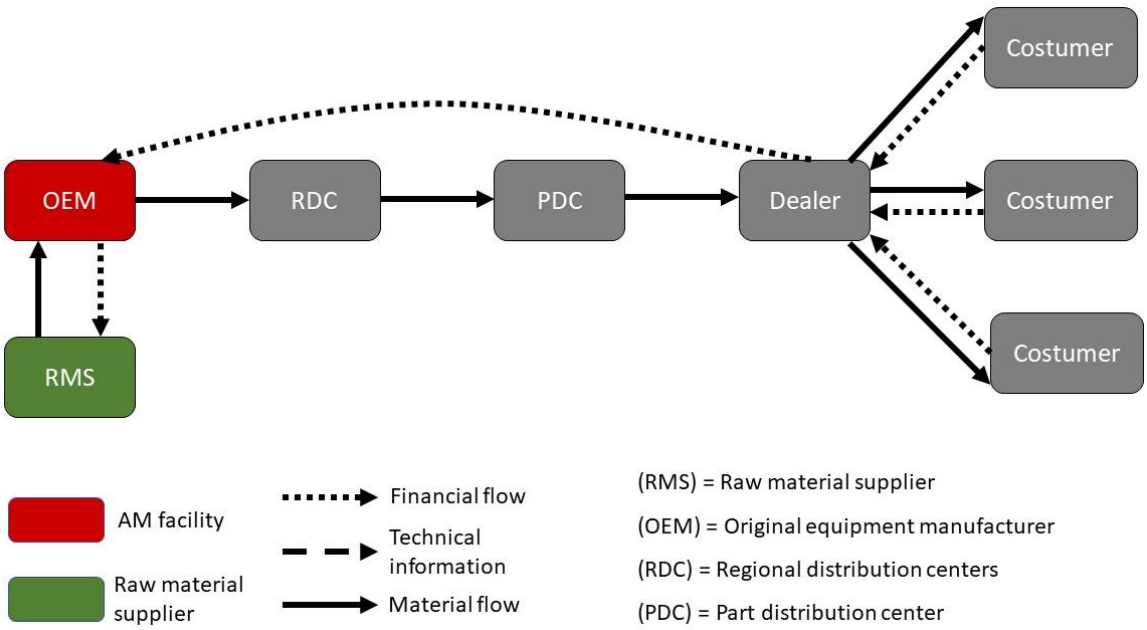

Figure 2.35: Centralized supply chain scenario, adapted from Eggenberger, Oettmeier and Hofmann (2018)

The conceptual research of the centralized supply chain approach leads the researchers to the following propositions:

- "A centralized implementation of additive manufacturing in the automotive spare parts supply chain is associated with bundling advantages in terms of capacity utilization, machine

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maintenance, and the sourcing of additive manufacturing materials" (Eggenberger, Oettmeier and Hofmann, 2018).

- "A centralized implementation of additive manufacturing in the automotive spare parts supply chain is favourable when short lead-times and low downtime costs are not key priorities for the OEM" (Eggenberger, Oettmeier and Hofmann, 2018).
- "A centralized implementation of additive manufacturing in the automotive spare parts supply chain is more suitable at the beginning when additive manufacturing is initially deployed, and little specific additive manufacturing know-how exists. At a more advanced stage, spare parts production with additive manufacturing can gradually be extended to decentralized locations" (Eggenberger, Oettmeier and Hofmann, 2018).

With the hybrid additive manufacturing implementation, the two research groups differ slightly in their approach. While Savastano *et al.* (2016) focusses on the hybrid manufacturing scenario of traditional and additive manufacturing, Eggenberger, Oettmeier and Hofmann (2018) analyses the hybrid supply chain scenario of a centralized (traditional manufacturing) and a decentralized (additive manufacturing) production.

The hybrid additive manufacturing scenario (2) from Eggenberger, Oettmeier and Hofmann (2018) proposes that the production is either implemented on RDC or PDC level, depending on the individual market characteristics. Concerning cost-effective production, the low demand markets can produce more centralized on RDC level, while large demand markets can produce on PDC level located closer to the point of use. Both situations combined are illustrated in Figure 2.36. Independent from the supply chain level, the additive manufacturing centre sources raw material and technical production data from the supplier and OEM. The distribution of the final part and the financial flow remains similar to the centralized scenario (1).

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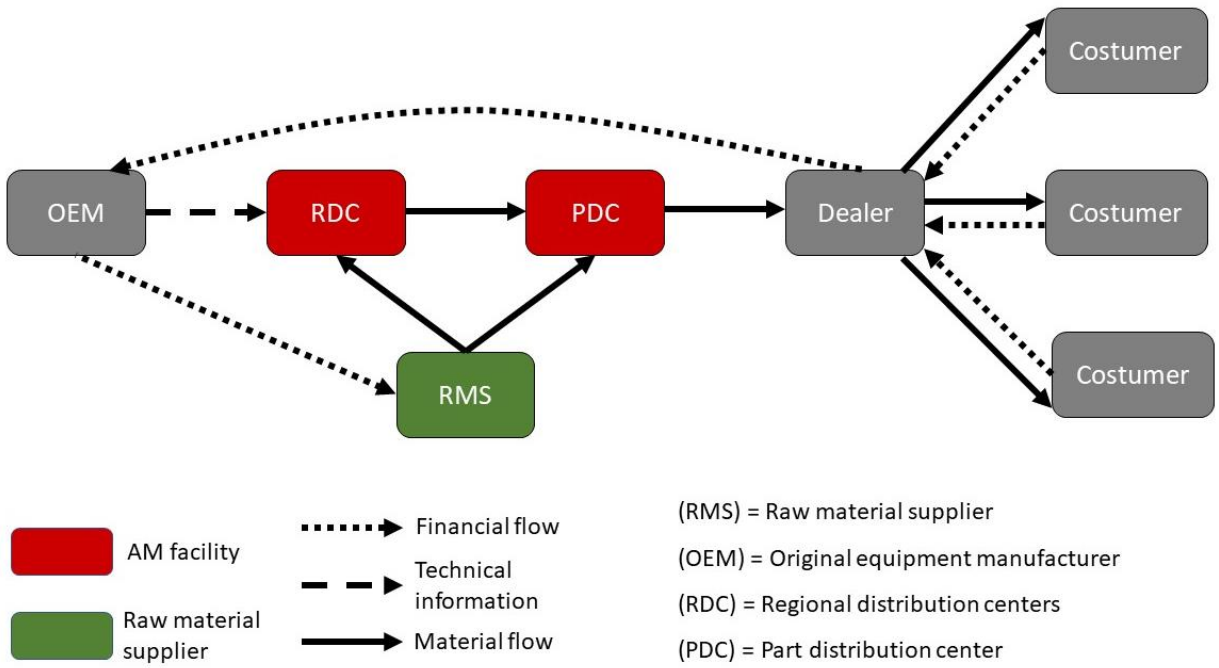

Figure 2.36: Hybrid supply chain scenario, adapted from (Eggenberger, Oettmeier and Hofmann, 2018)

The researchers conclude the following 3 propositions for the implementation of the hybrid supply chain scenario:

- "A hybrid implementation of AM in the automotive spare parts supply chain is likely to be an advantageous compromise between a centralized and a decentralized deployment if neither the demand level nor demand fluctuations or manufacturing lead-times are particularly extreme" (Eggenberger, Oettmeier and Hofmann, 2018).
- "A hybrid implementation of AM in the automotive spare parts supply chain is associated with a significant need to build up technical know-how since AM is introduced into a logistics environment" (Eggenberger, Oettmeier and Hofmann, 2018).
- "A hybrid implementation of AM in the automotive spare parts supply chain offers a higher flexibility and greater steering opportunities for the OEM to adjust to local demand patterns compared to a centralized deployment, while at the same time potentially retaining a high-capacity utilization" (Eggenberger, Oettmeier and Hofmann, 2018).

With the decentralized additive manufacturing approach (3) both research groups agree that printing spare parts at the customers' home is not feasible yet. Therefore, the dealer is the last feasible member in the down-stream supply chain for maximum decentralization. Figure 2.37 indicates the potential for simplifying the automotive supply chain for spare parts with additive manufacturing. The local dealer is the centre for material, information, and financial flows.

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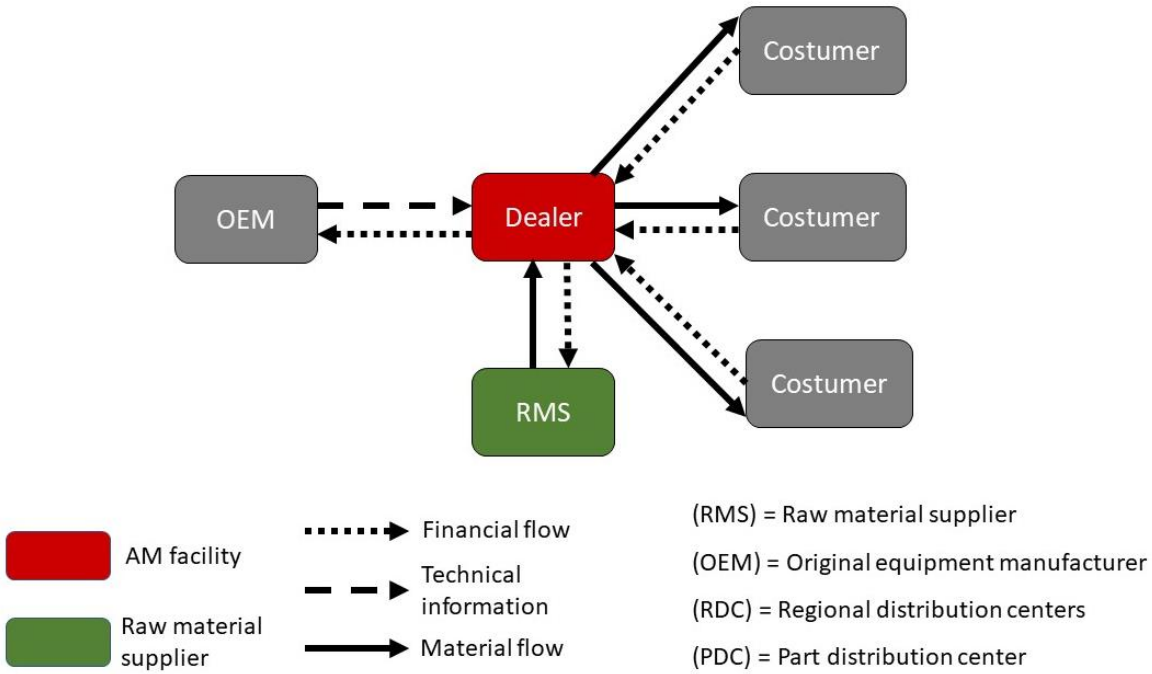

Figure 2.37: Decentralized supply chain scenario, adapted from Eggenberger, Oettmeier and Hofmann (2018)

Although this scenario seems to be streamlined, limitations for the implementation exist. The researchers also summarised the chances and risks of this approach in 3 propositions:

- "A decentralized implementation of AM in the automotive spare parts supply chain is impeded by the challenge to obtain a high-capacity utilization and high investment costs in AM equipment as well as the build-up of specific AM know-how" (Eggenberger, Oettmeier and Hofmann, 2018).
- "A decentralized implementation of AM in the automotive spare parts supply chain is associated with a reduction in transportation and inventory holding costs as well as less distortions in demand information" (Eggenberger, Oettmeier and Hofmann, 2018).
- "A decentralized implementation of AM in the automotive spare parts supply chain is associated with a higher customer service level. On the one hand, a faster response time can be offered and on the other hand, the customization of parts is facilitated, which can potentially lead to a price premium" (Eggenberger, Oettmeier and Hofmann, 2018).

The fourth scenario, the outsourcing of additive manufacturing (4), changes the role of the OEM and introduces a new member in the supply chain. The new member is a third-party manufacturing and logistic service supplier. In comparison to the decentralized scenario, the service provider takes the centre role over from the dealer. The OEM is not directly involved in the spare part production anymore. The role of the OEM is to control the process of the service supplier for quality assurance.

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Further, the OEM remains in the position responsible for research and development of manufacturing processes

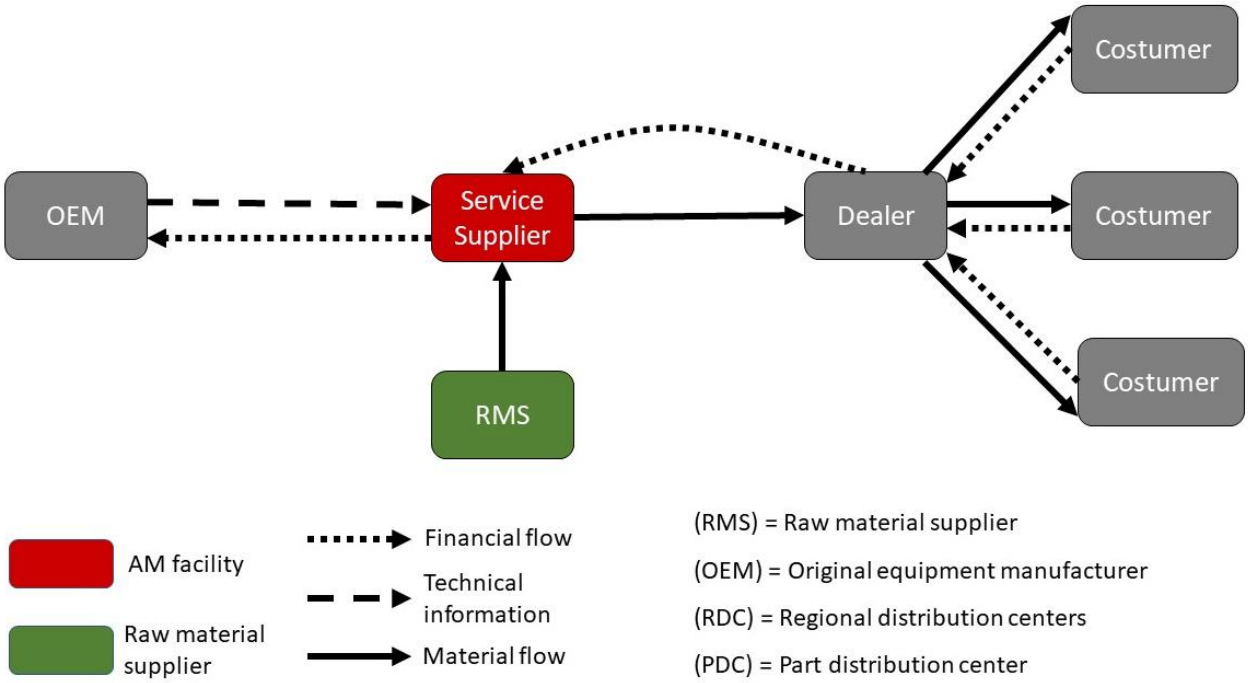

Figure 2.38: Outsourced supply chain scenario, adapted from Eggenberger, Oettmeier and Hofmann (2018)

The 3 propositions identified for the outsourced supply chain scenario are:

- "The outsourcing of automotive spare parts production with AM to an external provider is associated with a rising relevance of product development, quality control, and counterfeit protection tasks for OEMs" (Eggenberger, Oettmeier and Hofmann, 2018).
- The integration of new supply chain members provides service supplier potential for revenue and enables them to internalize an additional step of the automotive value chain.

The research of Eggenberger, Oettmeier and Hofmann (2018) reviewed 4 supply chain designs adopting additive manufacturing. Concluding, all designs are missing the high local or global demand for additive manufactured spare parts. In addition, the digital supply chain for design data from the OEM to dealers and service suppliers is not existing yet. To reach the opportunities of on-demand production and low inventories, all supply chain designs have to overcome challenges. Supply chain designs which have a decentralized approach, need to address the challenge of appropriate quality assurance systems. A further challenge for all supply chain designs is the low demand for additive manufactured spare parts resulting in an unexploited economy of scale. Other researchers state that the automotive serial production has to adopt additive manufacturing first to make additive manufacturing for spare parts economically feasible. However, a redesign of components according

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to additive manufacturing requirements was not included into the scenarios, which could have positive economic consequences. The researchers recommend that OEMs have to investigate the potential cases for the adoption of additive manufacturing. With that experience, OEMs will be prepared for the time when additive manufacturing is fully ready to fabricate a wide range of spare parts (Eggenberger, Oettmeier and Hofmann, 2018).

In addition to the two analysed research reports of Savastano *et al.* (2016) and Eggenberger, Oettmeier and Hofmann (2018), Delic and Eyers (2020) also conducted research on additive manufacturing for the automotive supply chain. In contrast to the two mentioned reports which are analysing feasible spare part supply chain designs, Delic and Eyers (2020) focuses "on how additive manufacturing technologies may affect the achievement of supply chain flexibility and performance in the automotive context" (Delic and Eyers, 2020).

The corresponding research report is providing a theoretical background for:

(1) additive manufacturing in the automotive industry,
(2) supply chain flexibility dimensions and,
(3) supply chain performance dimensions.

Based on the information from literature review on (1), (2), and (3), the researchers:

(4) built a research framework and introduced the research hypothesis,
(5) conducted a survey to test the hypothesis and,
(6) discussed and concluded the findings of this study.

The automotive industry together with the industrial machines and aerospace industry are the leader in the adoption of additive manufacturing for production purposes. In the early phases, automotive manufacturers utilized additive manufacturing (1) for building porotypes and in a later phase to produce final parts for vehicle concept models. Car manufacturers also use the new technology to produce components for in-series production, tooling and motorsport (Delic and Eyers, 2020).

The flexibility of a supply chain (2) is dependent on numerous independent factors which are difficult to measure. Based on previous literature published by other researchers, Delic and Eyers (2020) identified three main flexibility dimensions: manufacturing flexibility, postponement flexibility, sourcing flexibility

The performance of a supply chain (3), the second focus of this study, is dependent on the efficiency and effectiveness of supply chain processes. The efficiency itself is measured by the relation of input

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and output to reduce waste and cost. Effectiveness can be measured by service-related performance, for example, customer's satisfaction (Delic and Eyers, 2020).

The framework (4) of Delic and Eyers (2020) to evaluate "the effect of additive manufacturing adoption on the spare part supply chain flexibility and performance" is based on the findings of (1), (2) and (3). The framework gives the structure to develop the hypothesis that additive manufacturing is positively related to the automotive supply chain flexibility (Hypothesis 1) and the supply chain flexibility in turn has an impact on the supply chain performance (Hypothesis 2). Figure 2.39 illustrates the research framework and the hypothesis tested in this study.

Hypothesis 1 states that "additive manufacturing is positively related to the automotive supply chain flexibility". The hypothesis includes that additive manufacturing adoption is positively related to each subcategory, i.e. production flexibility, postponement flexibility and sourcing flexibility. The influence of additive manufacturing to each subcategory of supply chain flexibility is argued to be positive with references to other researchers:

- *Additive manufacturing adoption and production flexibility:* Achieving production flexibility is one of the main goals when changing technology in production processes. Production flexibility enables companies to meet customer demands of individualization, variations, and a wide product range. According to literature, a number of researchers state that additive manufacturing enables "time- and cost-effective adaptation of production processes, fast product and process configuration in the supply chain, new product development and performing difficult design geometries" (Delic and Eyers, 2020).
- *Additive Manufacturing adoption and postponement flexibility:* Offering variety and consumerization leads to-order production. To-order production in combination with short lead times require responsive production technologies and postponed operation. "The ability to produce a wide range of items directly from raw materials (e.g. resins or powders) means that additive manufacturing can support very high degrees of postponement in production or product assembly activities" (Delic and Eyers, 2020).
- *Additive Manufacturing adoption and sourcing flexibility:* "Sourcing flexibility concerns the capability of a company to adapt to market changes and its ability to increase supplier responsiveness, in such a way to increase or decrease order sizes without incurring extra costs or additional time to meet customer demand" (Delic and Eyers, 2020). In contrast to conventional manufacturing processes, additive manufacturing can produce efficiently at different levels of output without significant change in labour costs or capital investment.

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Hypothesis 2 continues the reaction chain of additive manufacturing, stating that the supply chain flexibility is positively related to the five performance dimensions in automotive supply chains. In general, the researchers argue that continuous improvements in the supply chain flexibility minimizes negative effects of product variety and customization on the supply chain performance. In detail, the researcher correlates the 3 supply chain flexibility dimensions with the 5 supply chain performance dimensions by providing evidence from literature. Figure 2.39 shows the connections identified. The following statements were made to underline the claimed correlations with the adoption of additive manufacturing:

- *Production flexibility*: Developing existing and new products or difficult and non-standard products introduction of new products to the market, short manufacturing lead times, or reduction in outbound costs may directly influence *cost* and *time*-based performance capabilities.
- *Postponement flexibility:* The flexibility in product design and configuration until receiving customers' orders and quickly responding to changes in the market, and increasing order fill rate, or by reducing inventory-holding costs and safety stocks may also influence *cost*, *time*, *reliability*, and *customer*-oriented performance capabilities
- *Sourcing flexibility:* "Enabling suppliers to operate efficiently at different levels of production volume and varieties (…), will likely affect *supplier-oriented* performance capabilities by enabling suppliers to quickly modify or introduce new products into the market" (Delic and Eyers, 2020).

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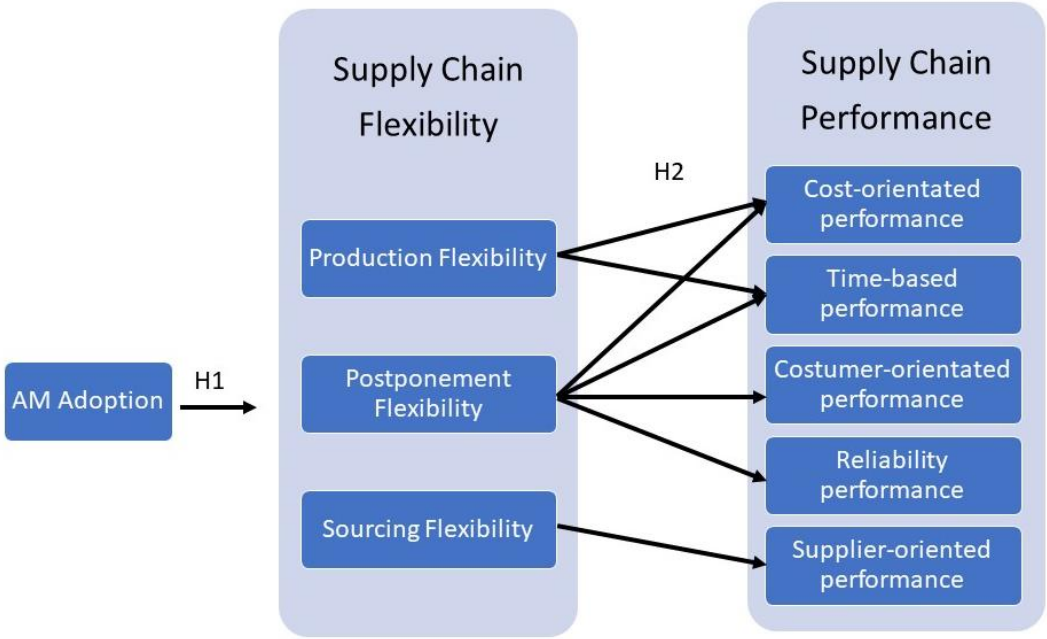

Figure 2.39: Research framework to analyse the effect of additive manufacturing on the supply chain flexibility and performance, based on Delic and Eyers (2020)

The researcher conducted a questionnaire survey (5) to collect quantitative data concerning the hypothesis. 128 small and medium (33 percent medium and 66 percent large companies) size companies from the European motor vehicle sector participated in that survey. Over 60 percent of companies have adopted additive manufacturing in any stage of the production process. The percentage of companies adopting additive manufacturing is rising with the companies´ number of employees and amount of turnover. Further, the researchers gathered data for the distribution of additive manufacturing applications across product lifecycle stages today and in 10 years. Nowadays, part visualization and prototyping are ranked first and second. Results that unexpectedly differed from literature information were additive manufacturing for direct part manufacturing was ranked relatively high and tooling was ranked relatively low. Data regarding the adoption of additive manufacturing in 10 years showed that product visualization stayed on the first place with the highest ranking. “An encouraging observation is that Additive Manufacturing adoption in direct part manufacturing generated almost the same average scores as the additive manufacturing adoption in prototyping” (Delic and Eyers, 2020).

In a second step, the data were used to test the hypothesised relationships by using the partial least square structural equation modelling framework. The analysis showed that the data support the hypothesis and the claimed relationships between additive manufacturing, supply chain flexibility and performance. In the discussion and conclusion (6) of the study, the researchers provide an

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overview of the results relating hypothesis H1 and H2. For Hypothesis 1, information from literature is corresponding with the findings of this research. “The results confirm a significant positive effect of Additive Manufacturing adoption on each supply chain flexibility dimension, with the strongest influence for production flexibility” (Delic and Eyers, 2020). Especially the flexibility in product mix and volume, new product development and customization were highlighted (Delic and Eyers, 2020).

Similar results as for Hypothesis 1 are recognized for Hypothesis 2. The researcher found a positive and significant influence of the supply chain flexibility on the supply chain performance. All 5 performance dimensions are positively influenced by an increase in flexibility. The researcher highlights that customer and supplier-oriented performance can be improved by adopting additive manufacturing. For example, benefits like the ability to respond to changes in customer demand can be achieved (Delic and Eyers, 2020).

Ending the study, the researchers conclude that additive manufacturing will find special applications in the automotive industry which is dominated by conventional-mass-production technology. Prototyping and new product designs in the early phase of an automotive series and the spare part production, on demand, near the customer in low volume at the end of an automotive series are applications with high potential (Delic and Eyers, 2020).

Conclusion

Although search terms relating to classic cars were included into the search string, none of the e-Databases contained any documents covering additive manufacturing for the spare part management of classic cars. Therefore, the focus of the literature review changed to the additive manufacturing of series and spare parts in the automotive industry to bridge the gap in literature. The aim of the scoping review of additive manufacturing for spare part management in the automotive industry was to find information in literature which can help answering the research questions of this chapter, identify the gaps in literature and to set a foundation of knowledge for further research.

For the first thematic group, literature was found regarding the additive manufacturing of automotive parts. Results show that the process of remaking existing parts consists mainly of the steps scanning, model repairing and improving, and additive manufacturing. For the first step, literature showed that the scanning of components can be done using photo cameras or smart phones. However, the software and hardware still need development for accurate dimensions from the scanning process (Bacciaglia, Ceruti and Liverani, 2020). The second step, the improvement of the digital model according to the properties of additive manufacturing, was identified as one of the main decision-making factors for a

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positive application case of additive manufacturing (Böckin and Tillman, 2019; Jankovics and Barari, 2019). A second main decision-factor is the feasibility of a material-process combination for the automotive industry (Jankovics and Barari, 2019).

For the second thematic group, literature was found regarding the spare parts supply chain adopting additive manufacturing. The supply chain performance measurement system of Chan (2003) was utilized to provide a structure for the analysis of the performance of the spare part supply chain in the automotive industry adopting additive manufacturing. Table 2.9 shows the information gathered from the literature. Comparisons are made with the conventional supply chain from Chapter 2.4.3.

Table 2.9: Summary of the supply chain performance in the spare part management of the automotive industry adopting additive manufacturing

	Sub level 1	***Sub level 2***	***Input form literature***
A. Quantitative	Cost	Distribution	• Reduction of parties involved in the supply chain
		Manufacturing & warehouse	• 4 Supply strategies (**SS**): ➢ **SS1**. Centralized production ➢ **SS2**. Decentralized production ➢ **SS3**. Hybrid production ➢ **SS4**. Outsourced production
	Resource utilisation	Labour, machine, energy	• Resource Utilisation differs throughout the supply strategies: ➢ **SS1**: Centralized Know-How, good capacity utilization, ➢ **SS2**: Short supply chain, weak capacity utilization ➢ **SS3**: Adjustable supply chain, good capacity utilization ➢ **SS4:** Low investment cost, good capacity utilization

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B. Qualitative	Quality	Customer dissatisfaction, customers response time,	• High response time • Individualization and variations opportunities • Customer process integration • Unrestricted batch sizes
		Stockout probability	• Low risk of obsolescence or stockout • Possibility for On-demand production
		Accuracy	• AM material and processes can meet automotive requirements, but raw materials and process options are still limited
	Flexibility	Output volume, output variety	• **SS1, SS3, SS4**: Medium/High output volume due to centralized manufacturing processes; medium variety • **SS2**: Low output volume due to decentralized production; High variety of products
		Modifications, integrating of new products	• Four supply chain strategies were found, more hybrid solution conceivable • **SS1, SS2, SS3**: Supply chain is limited to original parts • **SS4**: Independent productions allows Integration of third-party components
	Visibility	Time, accuracy	• No data found
	Trust	Consistency	• No data found
	Innovativeness	Launch of new products	• Car manufacturer is responsible in all supply chain strategies for the development of new products • Flexibility in production and distribution chain allows low effort launches
		Use of new technology	• Use of new technology is depended on the supply strategy (SS): ➢ **SS1, SS2, SS3**: Car manufacturer is responsible for implementing new technology into the supply chain ➢ **SS4**: External company responsible for the implementation of new technology

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The charting of the data from literature using the supply chain performance measurement model (Table 2.9) shows that most measure units are addressed. The Sub-level-1 category "Visibility and Trust" were the only issue not mentioned in the literature which entered this scoping review. However, many statements are predictions and need to be proven in practice. Furthermore, the low number of documents published in the e-Databases include that important information was not included in this scoping review.

2.6 **Chapter summary**

Since no literature was published in the major online libraries on the research subject "Additive manufacturing for the spare part management of classic cars", the literature review was split into three subsections. Firstly, the classic car market and the coherent spare part market was addressed. Information regarding the value of classic cars for owners and car manufacturers was identified. In addition to this, the market characteristics were analysed. However, no literature was found on the topic of spare part management of classic cars.

In the second literature review, the missing information of the spare part management of classic cars was derived from the spare part management of the automotive industry. Sufficient literature was found to create a knowledge base for spare part management in the automotive industry and to measure the supply chain performance. The topics planning, manufacturing, warehousing, and distribution of spare parts were covered.

The feasibility of using additive manufacturing to produce spare parts and the impact on the supply chain performance of spare parts was addressed in the third literature review. Literature states that spare parts can be produced with additive manufacturing. However, there are spare parts which are more suitable than others, underlying several factors. The information from literature on the supply chain performance can be used to measure the impact of additive manufacturing.

Overall, each literature review revealed relevant information which can influence the impact of additive manufacturing on the spare part management of classic cars. Therefore, this information from literature can be grouped and considered as measurement variables. The impact of additive manufacturing on the spare part management of classic cars is dependent on these measurement variables.

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Chapter 3
Research Methodology

3.1 Introduction

The literature review on the spare part management of classic cars in Chapter 2, set a base of knowledge for further research and identified gaps in literature. The purpose of Chapter 3 is to identify an appropriate research design and methodology to address the problem statement and close the gap in literature. The conduct of the methodology and its included methods is then outlined in Chapter 4 to Chapter 6.

3.2 Research design

The goal of an appropriate research design is to determine the impact of additive manufacturing on the spare part management of classic cars. To fulfil that objective, an exploratory research design was chosen. An exploratory research design is used when the research topic has not been researched entirely. It explores a problem and helps to formulate the problem exactly (Sarstedt and Mooi, 2019). Exploratory research is intended to provide a range of causes and alternative options for a solution of a specific problem, other than a conclusive research, which is aimed to identify the final solution to an existing research problem (Saunders, Lewis and Thornhill, 2019).The exploratory research design was chosen over the conclusive research because the research topic has not been researched before. The literature review revealed that additive manufacturing can be used to produce spare parts. However, no literature was found which combines additive manufacturing and classic car spare parts.

3.3 Research methodology

The research methodology represents the central guideline of this research approach. The objectives for this research project were stated in Chapter 1.3. Two out of the three research objectives were identified to be relevant for the methodology of this research study:

- Investigate the improvement potentials and explore the feasibility of producing spare parts using additive manufacturing

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- Design an implementation approach for the use additive manufacturing to produce classic car spare parts and estimate the potential impact

In the context of an exploratory research design, other published research projects were searched to identify a feasible research methodology for this research project, which addresses all above mentioned objectives. The search was guided, same as the literature reviews of Chapter 2, by the Literature Scoping Review from Davison (2019).

3.3.1 Literature review: research methodology

The aim of the scoping review for the section "Research Methodology" is to find articles which use a methodology that includes the above-mentioned research objectives. A scoping literature review was conducted to analyses a large amount of research methodology and to narrow it down to the most relevant ones. In the following, the familiar five step process of the scoping literature review is conducted.

Step1: Identifying the research questions

The research objectives were defined in the research proposal in the initial phase of the research project. It would be feasible to adjust the objectives throughout the research process of gathering knowledge. In this case however, the objectives could remain. Based on these objectives, the following research questions for this literature search were defined:

Reserch Question 1	Are the identifyed measurement variables from the literature review approriate?
Reserch Question 2	Which method can be used to gather behavioral data from classic car owners?
Reserch Question 3	How can the measurement variables be combined in a ranking method?
Reserch Question 4	How can the potential methodology be validated?

Step 2: Identify relevant studies and statistics

A scoping review recommends the initial search to be as comprehensive as possible, from a wide range of sources (Arksey and O'Malley, 2005). Basic exclusion criteria based on the date of

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publication are not given to increase the number of articles. For the same reason, all sources written in both English and German were considered. The final search strategy included e-databases such as SAGE, Science Direct and Springer Link. These Databases were accessed through the membership of “University of Stellenbosch” and “Hochschule München”.

Searching was executed using the following two search strings, one in English and one in German:

- “Spare part” OR “part” OR “component” AND “ranking” OR “measure” OR “select” AND “additive manufacturing” OR ”3D-printing”;
- „Ersatzteil” OR „Bauteil” OR „Komponente“ And „Rangliste” OR „Bewertung“ OR „Wahl“ And „3D-Druck” OR „Additive Manufacturing“;

Step 3: Select studies and statistics

The PRISMA-ScR flow diagram was used as a template to illustrate the record selection process for the review (Figure 3.1). In the Identification, phase 54 records were found in the four electronic databases. The title and abstracts of these records were screened in phase two. In this phase, 50 records were excluded because their content did not suit the research questions of this literature review. The resulting 4 records were assessed, in the third phase, in a full-text analysis to identify whether the content is contributing towards a base of knowledge, or whether the record has to be excluded. In the last phase, the only remaining record was analysed for the inclusion in this scoping literature review.

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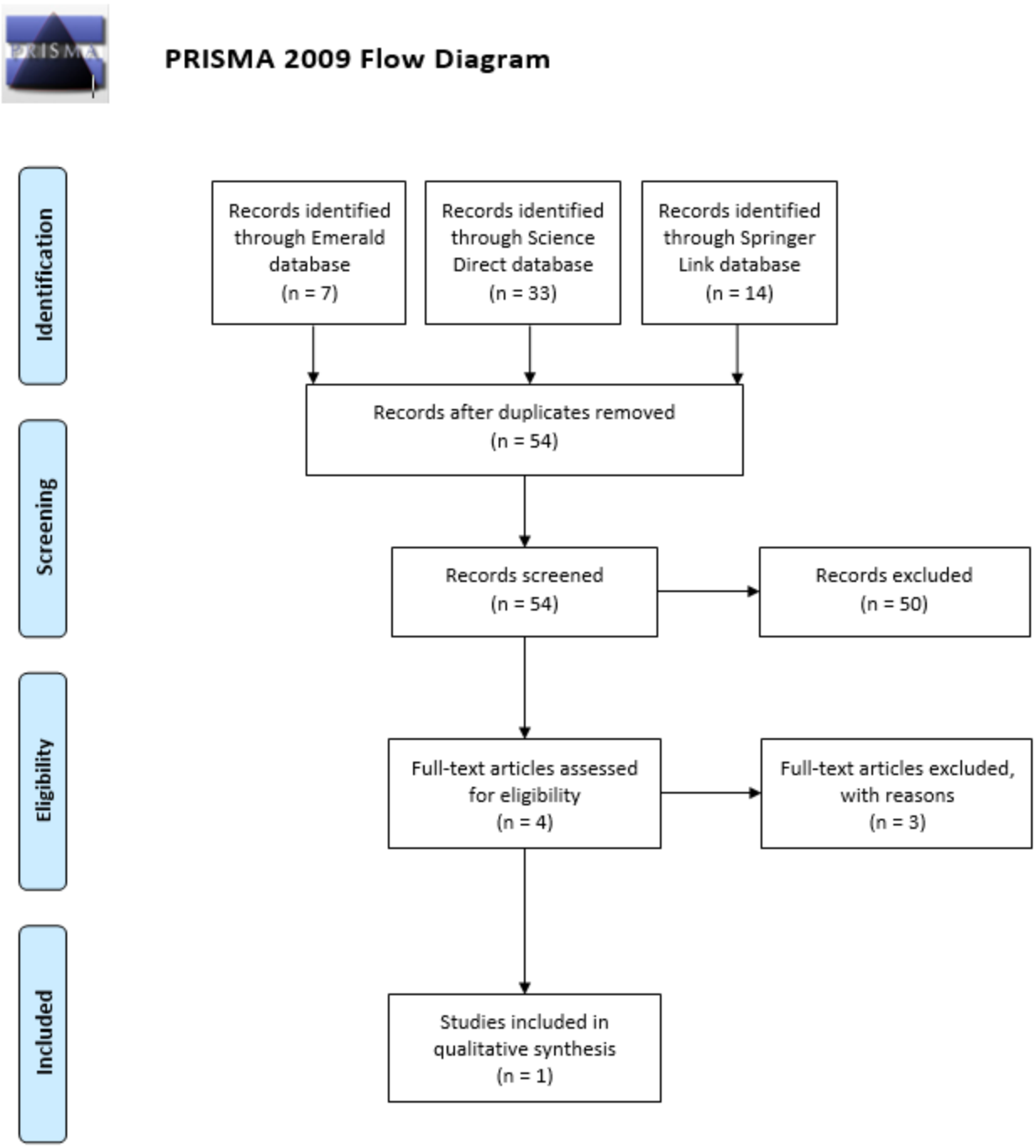

Figure 3.1: PRISMA-ScR Flow Diagram for the literature review for a feasible research methodology, adapted from Rouse (2016)

Step 4: Chart the data

Since only one document entered the final review, the charting of the data can be done in a shortened process. The journal article of Nils Knofius was published in the year 2016, in the database of Emerald. The research was conducted at the University of Twente in the Netherlands. The content of this article was grouped into the fields “ranking method”, “additive manufacturing” and “spare parts”.

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Step 5: Collate, summarise, and report the results

Knofius, van der Heijden and Zijm (2016) developed a ranking method "to identify economically valuable and technologically feasible business cases" for additive manufacturing. The ranking method is designed in such a way that it can be customized towards company or database specific characteristics. The method can be described in five steps:

(1) Select spare part assortment
(2) Identify spare part attributes
(3) Link attributes to potential for additive manufacturing
(4) Score spare parts according to attributes
(5) Validate the ranking method

In step one (1), the researchers recommend focussing on a selected spare part assortment of a given database. Focussing on one subset of parts with similar characteristics will simplify the following process steps. In step two (2), the database is analysed to identify relevant spare part attributes for the ranking method. The relevant attributes are then linked to the improvement potential when using additive manufacturing in step three (3). Some attributes were identified as Go/No-Go criteria. These attributes are, for example, technological constraints of additive manufacturing. In the ranking process (4), each part of the assortment is scored individually according to its value in terms of the attributes. To include the level of importance of an attribute, the researchers have addressed every attribute with a weight. In their case, the importance of an attribute is based on the company goals. Go/No-Go attributes are not assigned with a weight. After all, based on the attribute weights and values, weighted average scores are calculated for each spare part.

In a final step (5), the researchers applied the ranking method to a real case scenario. A spare part database, consisting of 40,330 aeroplane parts, was used. The outcome of the ranking was that 1,141 parts are technologically feasible and economically beneficial. The outcome of the ranking was validated by comparing the calculated scores of a sample of parts with the opinion of the implementation manager for additive manufacturing technologies. Results show that the managers assigned most parts with a lower improvement potential when using additive manufacturing than the ranking. However, the parts scoring the highest scores in the ranking also scored highest in the ranking of the managers. The same correlation could be observed with parts scoring lowest in the ranking. These parts were also rated low by the managers. Overall, the researchers concluded that no adjustments had to be done to the ranking method. However, for future research efforts, Knofius, van

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der Heijden and Zijm (2016) recommend extending the proposed method by considering possible design improvements.

3.3.2 Customizing the research methodology

The presented research methodology approach by Knofius, van der Heijden and Zijm (2016) includes all objectives set for this research. However, due to various reasons, this methodology had to be customized. In the following section, the steps (1-5) were checked to determine whether the approach had to be customized for this research project. If changes were made, a reasoning was provided. Steps 6 and 7 were performed in addition to Knofius, van der Heijden and Zijm (2016)'s method to meet the stated research objectives.

(1) Select spare part assortment

The research of Knofius, van der Heijden and Zijm (2016) suggest using a database of an original equipment manufacturer (OEM), service provider or asset user. The first source considered in an attempt to get a database of classic car spare parts was a car- or component manufacturer. Two employees from two German car manufacturers were contacted. One employee, and the responsible classic department, were interested in a collaboration. However, due to obligations of secrecy it was not allowed to use companies' data for external research projects.

The option of sourcing a database from a database-service-provider was considered next. The word "Service provider" could be a variety of companies in the supply chain of classic car spare parts. To contact a company, without a personal relationship to this company, and request for a database with sensitive information was classified as unprofessional. A service provider for databases could also be a company who sells databases via the internet. Through Google search, appropriate databases of these service providers were searched. However, no database was found.

The next option considered was the asset users. The users of classic car spare parts are primarily the owners of classic cars. The classic car owners were considered as the best source to gather data about the spare part management of classic cars. It was realistic to conduct a survey with classic car owners to receive primary data on spare parts and its relevant spare part attributes. The process used for the survey will be discussed in Chapter 4.2

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Creating a customized database enables the user to choose which spare part assortment should be focused on. For this research methodology, spare parts of classic cars were selected which are not satisfying customer demands. To bring characteristics of classic car spare parts into the spare part management context of the literature review, classic car spare parts are in the outlet phase of a car series' life cycle. At this point, the series is more than 10 to 15 years out of production, and the warranty of the vehicle is expired. The car manufacturer has no delivery obligation for spare parts towards the customer. This means that both dependent - and independent supply chain channels could be considered. Furthermore, all production and recycling approaches of spare parts were considered. In addition to the time-limited, wear and weak link part, accessory parts were also considered. However, the focus of the database was to gather spare parts which did not satisfy customers expectations. For example, a spare part could be available on the market, but the quality of the delivery time was insufficient for the customer.

(2) Identify spare part attributes

Since this research got its database from a self-conducted survey, the choice of spare part attributes was not determined by an existing database. Through the literature review of Chapter 2, information was gathered on the topics "Classic car market", "Spare part management" and "Additive manufacturing for spare parts". This information was identified as measurement variables which were used to determine the impact of additive manufacturing on the spare part management of classic cars. Therefore, these measurement variables set the base for the ranking method. A measurement variable qualifies for the ranking method if the attribute could be transformed into the survey question. Classic car owners might have different levels of knowledge on the spare part management of their classic cars. A question was included into the questionnaire if a classic car owner was expected to have the knowledge to answer. Table 3.1 lists the measurement variable from the literature reviews.

For the further ranking process, the measurement variables were put into groups of similar topics. These groups were named individually and fell under the name "spare part attributes". These spare part attributes were relevant in the subsequential ranking process.

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Table 3.1: Measurement variables identified in the literature review, grouped to spare part attributes

		Measurement variables from Literature			
Spare Part Attributes (Y)	Demand rate	Age of car		Value of car	
	Availability	Difficulty to find spares	Original part availability		Replica part available
	Delivery time discrepancy	Delivery time offered		Delivery time expected	
	Replacement urgency	Replacement urgency			
	Customers order cost	Customers' location			
	Innovation Potential	Innovation potential			
	Individualization potential	Individualization potential			
	Openness for AM	Level of knowledge on AM	Trust in AM	Willingness to buy AM parts	Material deviation
	Mechanical stress	Mechanical stress			
	Size	Part size			
	Material	Material type			

(3) Link attributes to potential for additive manufacturing

The spare part attributes were linked to the potential of additive manufacturing to improve the spare part management of classic cars. The potential of additive manufacturing was identified through the literature review in conjunction with the supply chain performance measurement model, and through the research of Knofius, van der Heijden and Zijm (2016). Table 3.2 visualises the potentials of additive manufacturing (X) if a spare part attribute (Y) has the value (Z). The values of the spare part attributes were set on the optimal condition for additive manufacturing, e.g., low demand rates are considered to have higher potential for utilizing additive manufacturing than high demand rates. The spare part attributes "Mechanical stress", "Size" and "Material" are so-called Go/No-Go attributes which are implemented to represent the technical limitations of additive manufacturing. These attributes have a fixed limitation and are, therefore, not underlying the weighting method.

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Table 3.2: The influence of spare part attributes on the improvement potential utilizing additive manufacturing

		Improvement potential using additive manufacturing (X) / Customer goals					
		Reduce cost		Reduce downtime		Additional customer's satisfaction	Increase supply chain flexibility
		Reduce manufacturing cost	Reduce order cost	Reduce delivery time	Reduce stock out probability		
Spare Part Attributes (Y)	Demand rate	Low	Low	Low	Low		Low
	Availability	Low	Low	Low	Low		Low
	Delivery time discrepancy	Long		Long			Long
	Replacement urgency		High	High			
	Customers order cost		High				
	Innovation Potential				High	High	
	Individualization potential					High	
	Openness for AM					High	High
	Mechanical stress	Go/No-Go					
	Size	Go/No-Go					
	Material	Go/No-Go					

*<u>Note:</u> Please read Table 3.2. in the following way. If the **Spare Part Attribute (Y)** is **Value (Z)**, then additive manufacturing has the **Improvement Potential (X)**. For example, if the **Demand rate** is **Low**, additive manufacturing has the potential to **Reduce Manufacturing Costs.***

The correlation between the spare part attributes, the collected data from the survey and the improvement potential of additive manufacturing is explained in the following section.

The "**Demand rate**" symbolizes the expected demand for a spare part over a certain period. The demand rate is calculated by the vehicle's value and the age of the car. It is presumed that the higher the value of a car, the lower the number of cars existing. The same connection can be made for the age of the car. It is concluded that the number of existing cars is related to the level of demand for spare parts. If the demand for spare parts is low, manufacturing costs per unit are high, the order costs are high, and the delivery time is long due to centralized warehousing. Centralized warehousing is also connected with a low supply chain flexibility. Additive manufacturing has its potential in the low

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volume production and has, therefore, the potential to reduce the manufacturing cost. With a decentralized production utilizing additive manufacturing, order cost, delivery time and the supply chain flexibility can be improved.

The "**Availability**" of a spare part is calculated from the overall level of difficulty to find spare parts for a vehicle, the availability of the original part and the availability of a replica part. If the availability of the spare part is low, it is presumed that the manufacturing costs are too high for an economic extra production. The order costs are high due to the low availability at local sources, which also results in long delivery times. Limited availability also results in limited sourcing options, which decreases the supply chain flexibility and results in a high chance of stock out probability. The above-mentioned influences of low spare part availability show the potential for utilizing additive manufacturing.

The "**Delivery time discrepancy**" is a calculated value of the delivery time offered by the supplier and the delivery time expected from the customer. A high delivery discrepancy might be caused by limited capabilities for manufacturing postponement. To accommodate the delivery time expectations, smaller batch sizes must be manufactured, which results in a higher proportion of tooling cost per part. The discard for tooling with additive manufacturing relates to a decrease in manufacturing cost and delivery time. In addition to this, the flexibility in production schedule increases the supply chain flexibility.

The "**Replacement urgency**" is implemented to accommodate parts with a high urgency for replacement. This could be, for example, parts which are necessary for the usability of a vehicle or to pass a roadworthy test. Due to the focus on short term demand, this spare part attribute does not consider the manufacturing process and focuses on the delivery process. A high urgency for replacement requires fast transport over long distances and individualized transport on the "last mile". Additive manufacturing implemented at a decentralized level can decrease the delivery cost and delivery time by discarding major transportation activities.

"**Customer order cost**" is related to the location of the customer. It is presumed that the availability of spare parts for classic cars is high in the country where the car was manufactured, where the car brand has its headquarters, or in the major industrial countries. Additive manufacturing implemented at a decentralized level has the potential to reduce order costs in countries where the next available spare part is far away. In addition to this, customer duties can be eliminated if the part is produced domestically.

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The "**Innovation potential**" of a part is sourced straight from the survey response. A high potential for innovation is correlated with a high risk for obsolescence. Obsolete spare parts have a high potential for stockout because the demand is considered to be low. A spare part utilizing the capabilities of additive manufacturing for part improvements can lead to additional customer satisfaction.

The "**Individualisation potential**" of a part is also sourced straight from the survey response. Using additive manufacturing for individualised parts can lead to additional customer satisfaction.

The "**Openness for additive manufacturing**" of the customer is calculated from the level of knowledge about additive manufacturing, the trust in additive manufacturing, the willingness to buy parts produced with additive manufacturing, as well as the openness to accept a change in material. A high openness can lead to meeting customers' expectations for adopting new technologies, which results in achieving additional customer satisfaction. Furthermore, a high openness for additive manufacturing simplifies the implementation of "hybrid manufacturing", which is the production with conventional manufacturing methods and additive manufacturing at the same time. Hybrid manufacturing would lead to an increase in supply chain flexibility due to an increase in sourcing options.

"**Mechanical stress**", "**Size**" and "**Material**" are so-called "Go/No-Go" criteria. These criteria are implemented to exclude parts which are not feasible for additive manufacturing at this stage.
A high "Mechanical stress" on the part usually requires a specialized production method. At this early stage of the development of additive manufacturing, it is assumed that parts with a low mechanical stress level are better suited for an initial production run than parts with a high stress level. Therefore, this research will assess safety critical parts and parts with high mechanical or thermal requirements.
The "Size" of a part suitable for additive manufacturing is limited by the manufacturing space of the machine. Components can be divided into sub-components for the manufacturing process and assembled afterwards. This option will be considered in the assessment of spare parts.
The choices of "Material" for additive manufacturing are limited. If a material is not suitable for additive manufacturing and no replacement material can be found, the part is unfeasible for production with additive manufacturing at this stage.

The research of Knofius, van der Heijden and Zijm (2016) took company goals into consideration to weigh the spare part attributes according to their importance for a company. In this research however, the database was collected from the customers of the spare part market. Therefore, customer goals

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were considered in this research, instead of company goals. The research approach was to collect data on customer goals through the same research method as the database was collected through. The three Go/No-Go criteria were excluded from the weighting process. They described the technological feasibility of additive manufacturing, and were, therefore, independent from customer goals.

To assign a weight to customer goals according to the selected spare part attributes, customer goals were based on the improvement potentials(X) of additive manufacturing. For the further ranking process, the improvement potentials "Reduce manufacturing cost" and "Reduce order cost" were combined to the customer goal, "Reduce cost". The improvement potentials "Reduce delivery time" and "Reduce stockout probability" were combined to the customer goal, "Reduce downtime". The other two customer goals, "Additional customer satisfaction" and "Supply chain flexibility", remained ungrouped, as shown in Table 3.2.

(4) Rank spare parts according to attributes

The scoring of the spare parts according to their potential for additive manufacturing was done in a similar format as the research of Knofius, van der Heijden and Zijm (2016). Their 2-step ranking process, consisting of "Scoring parts according to attribute and weighing of attributes", needed to be slightly modified and an additional step must be implemented. Figure 3.2 illustrates the extension and modification of the ranking process.

In contrast to Knofius, van der Heijden and Zijm (2016), in this research, the spare part attributes were not sourced directly from the database. As mentioned in this Chapter under Step (2), the attributes were calculated from measurement variables. The additional step consisted of unifying the data of the survey on the measurement variables into one scale-format. The survey data were collected in different formats. Therefore, the survey responses had to be unified in a scale-format for the further calculation process. The unified scale-format represented the effect of a measurement variable on the potential of additive manufacturing for this part. For example, a high score on the unified scale should represent, for any measurement variable or attribute, a high potential for additive manufacturing. The linking of measurement variables to the potential of additive manufacturing worked according to Step (3) explained in chapter, "Linking attributes to the potential of additive manufacturing".

In the second step of the scoring of spare parts, the average of measurement variables was calculated. The result of this equation was the score of the attributes. In step three, the attribute scores were multiplied with their weight, and finally, all attributes' scores were summarised to the overall score.

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The part with the highest score should have the highest potential for additive manufacturing according to this ranking method.

In Chapter 4.3, the calculation of the scores with the survey data is explained and a detailed example of the scoring method is presented.

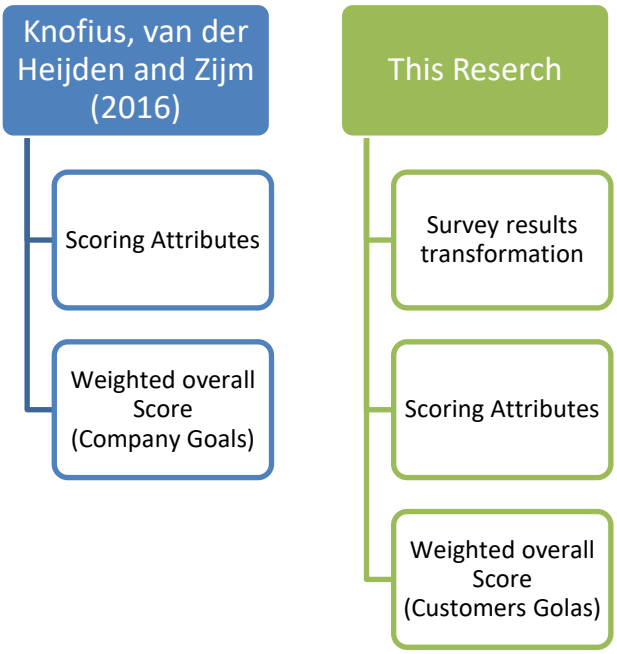

Figure 3.2: Processes to score spare parts according to their attributes scores

(5) Validation of the Ranking Method

Knofius, van der Heijden and Zijm (2016) used for the validation of the ranking method implementation managers for additive manufacturing. The researchers compared the outcome of their ranking method with the opinion of the managers. Since the methodology was customized for the ranking of classic car spare parts, this ranking method was validated as well. A similar validation process to the one in the aforementioned research project seemed feasible. However, the validation process needed to be customized to suit the circumstances of this project.

For the validation process, experts had to be found who have knowledge on the spare part management of classic cars, as well as on additive manufacturing. Furthermore, a method was needed to gather the opinions of these experts. Both the identification of suitable experts, and the search for a feasible validation process, is described in Chapter 4.4.

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(6) Case study

In contrast to Knofius, van der Heijden and Zijm (2016), this research added an additional case study. The aim of this case study was to gain experience in using additive manufacturing to produce classic car spare parts. The conduct and the outcome of the case study is presented in Chapter 5

(7) Implementation approach for additive manufacturing

As the last step of the modified methodology, the information gathered from the literature review, ranking process, validation, and case study are discussed in Chapter 6. Furthermore, recommendations for an implementation approach for the inclusion of additive manufacturing for the spare part management of classic cars are discussed.

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Chapter 4
Surveys and Analysis

4.1 Introduction

Chapter 3 explained the ranking methodology of Knofius, van der Heijden and Zijm (2016) being the overall methodology used for this research project. The ranking methodology has been customised towards both modifying the 5 steps determined by Knofius, van der Heijden and Zijm (2016) and adding two further steps. These seven steps of the modified ranking methodology were further detailed, and each step could be subdivided into different processes using various methods. These specifications and relevant processes and methods used are described in Chapter 4 to Chapter 6.

4.2 Online market survey

This survey is linked to step 1 ("Select Spare Part Assortment") of the modified methodology. The gathering of data directly from the source is called primary market research.

Published literature was used to argue and verify the choice for appropriate methods used in this survey. The large variety of literature published was narrowed down to two main publications, which were chosen for different reasons. First, Bryman (2015) was chosen because his publication is designed for students of marketing and business studies to understand and apply research methods. "It introduces the reader to the core values, concepts and methods involved in doing research" (Bryman, 2015). Secondly, the paper by Sarstedt and Mooi (2019) was included as it guides the reader in conducting market research. The researchers state that market research "can help organizations by providing answers to questions firms may have about their customers and competitors; answers that could help such firms improve their performance" (Sarstedt and Mooi, 2019). This definition of a market research was identified as an applicable method to answer the research question. Sarstedt and Mooi (2019) introduced a process on how to conduct primary market research. The process steps are illustrated in Figure 4.1. Every process step is addressed in its own chapter.

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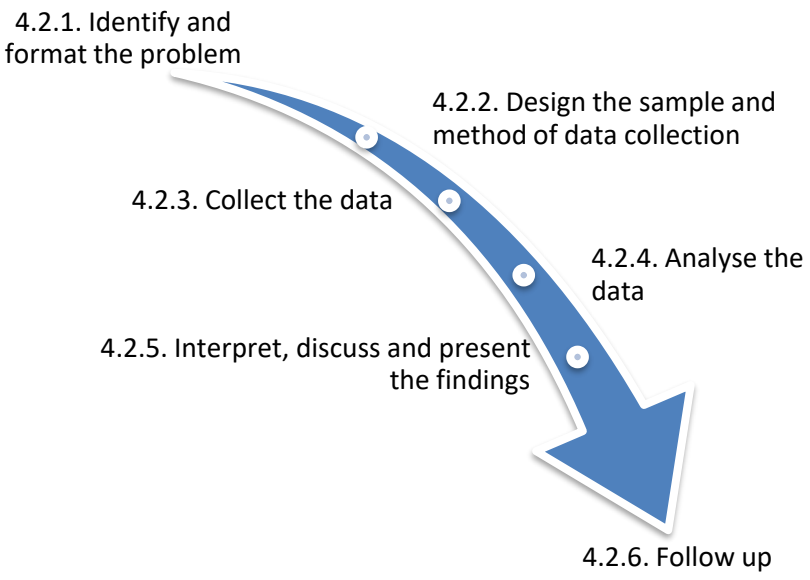

Figure 4.1: The market research process, adapted from Sarstedt and Mooi (2019)

4.2.1 Identify and format the problem

The first step in the Sarstedt and Mooi (2019) market research process of gathering primary research data, is the identification of the research problem. The research problem can result either from "marketing symptoms" or from "marketing opportunities". Marketing symptoms are described as a problem a company or organisation in a market is facing, for example, a decrease of market shares. Marketing opportunities on the other hand are not caused by a problem, but are a result of a market potential, for example, an emerging market opportunity (Sarstedt and Mooi, 2019).

The information from the literature review of Chapter 2 identified that original equipment manufacturers and independent manufacturers are competing for spare part market shares. The adoption of new technology could shift the market share towards the companies who are implementing the new technology. The threat of staying behind in technology development could be described as a "marketing symptom" (Sarstedt and Mooi, 2019). However, based on the literature review, the "marketing potential" was identified as the main driver for a successful integration of additive manufacturing to produce spare parts for classic cars. To manufacture spare parts on demand, close to where demand arises, and for a competitive price, and in a quality comparable to conventional manufacturing, is the best-case scenario.

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4.2.2 Design the sample and techniques of data collection

Step two of the Sarstedt and Mooi (2019) market research process was called "Design the Sample and Method of Data Collection". The two types of data can be collected, primary and secondary data. While the literature review focused on the gathering of secondary data from literature, this framework is used to gather primary data from self-conducted research. Bryman (2015) provides a decision-making structure for social surveys. Figure 4.2 illustrates this structure.

To achieve the aim of building a database, as many respondents as possible were invited and processed. Conducting a structured interview with every participant can be expensive and time-consuming (Bryman, 2015). Therefore, in this research, a self-completed questionnaire was identified to work best to achieve a database of many respondents. Furthermore, an internet-based survey was chosen to make international participation most convenient. The alternative "supervised" self-completable questionnaire was not chosen because the supervision of participants was not identified as relevant. The "postal" option was not chosen, because it was seen as more costly and time-intensive than the internet-based survey. Lastly, Bryman (2015) gives the option to conduct the survey via mail or via a web page. Stellenbosch University provides software for web page surveys. This software provides a variety of customization of the survey. Therefore, the web page was chosen over the Email survey.

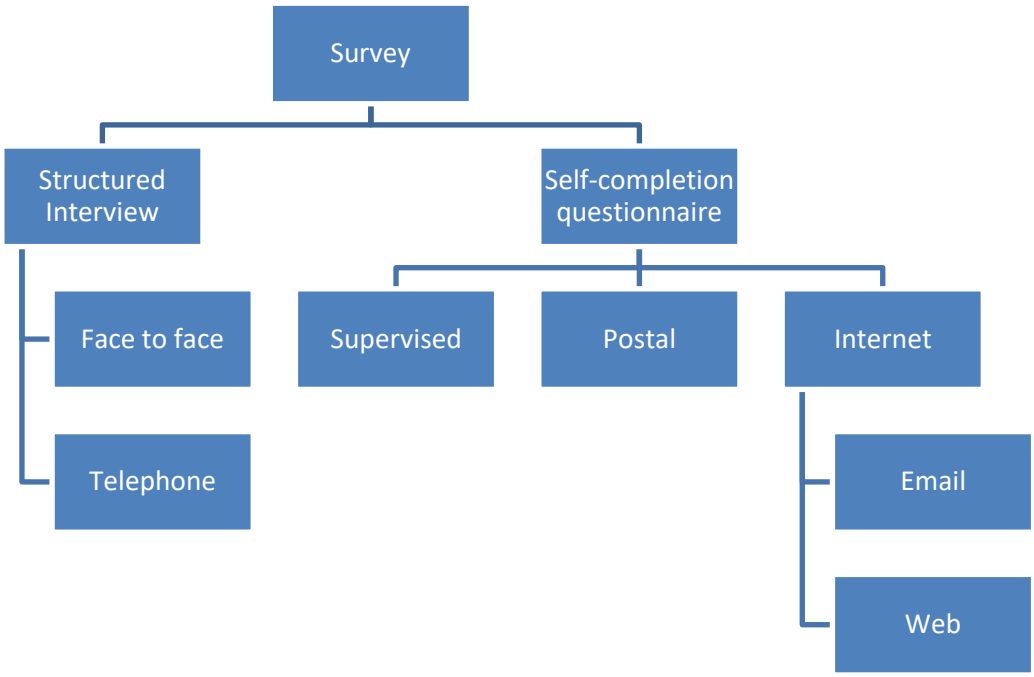

Figure 4.2: Main models of administration of a survey, adapted from Bryman (2015)

Bryman (2015) suggests for self-completed questionnaires, a clear presentation and clear instructions on how to respond must be provided. To follow these instructions, the questions were grouped

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according to their content. Each group of questions was presented on a different page of the survey. This layout allowed to give instructions regarding the questions on the page. Table 4.1 shows the five topic groups of the survey.

The goal of the survey questions was to create a database of classic car spare parts with sourcing problems to rank them according to their potential for additive manufacturing. For this ranking process, questions addressing the measurement variables from Chapter 3.3 were created. To identify the parts and their functionality, questions regarding the brand of the vehicle and the assembly group of the spare part were asked. Furthermore, the owners' problems with sourcing the spare part were identified. In addition, characteristics of the spare part which might influence the success of additive manufacturing were found out. Last, customer goals and customers openness towards additive manufacturing were asked.

Bryman (2015) highlights the importance of choosing an appropriate scale for the responses. The 5-point Likert scale is the most recommended scale for a survey if the question allows the use of this scale. This decision model was adapted for this research as well, i.e. if the question allows the use of the 5-point Likert scale, the scale will be used. If the scale is not appropriate for a question, the next best format was identified.

Table 4.1: Format and scale of questions asked in the market survey

Num.	***Topic / Measurement variables***	***Format / Scale***	***Conditional question***
1	Personal information		
1.1	Participant's location	Select answer	
2	Ownership information		
2.1	Make	Select answer	
2.2	Model	Select answer	
2.3	Model year	Select answer	
2.4	Value of car	5-point scale	

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Num.	*Topic / Measurement variables*	*Format / Scale*	*Conditional question*
3	Spare part – unsatisfied demand		
3.1	Spare part sourcing difficulty	5-point scale	
3.2	Assembly group of part	Select answer	
3.3	Parts name	Select answer	
3.4	Detailed parts name	Text box	
3.5	Available at dependent supplier	Yes/No	
3.6	Sourcing problem	Select answer (multiple)	If 3.5 = Yes
3.7	Available at independent supplier	Yes/No	
3.8	Sourcing problem	Select answer (multiple)	If 3.7 = Yes
3.9	Urgency for spare	5-point scale	
3.10	Part size	5-point scale	
3.11	Material type	Select answer (multiple)	
3.12	Expected delivery period	5-point scale	
3.13	Offered delivery period	5-point scale	
3.14	Design improvements	5-point scale	
3.15	Individualization potential	5-point scale	
4	Customers goals		
4.1	Low price vs. short delivery time	100-point (comparison)	
4.2	Low price vs. high reliability	100-point (comparison)	
4.3	Low delivery cost vs. short delivery time	100-point (comparison)	
5	Additive manufacturing		
5.1	Knowledge on additive manufacturing	5-point scale	
5.2	Trust in additive manufacturing	5-point scale	
5.3	Purchase intention of additive manufactured parts	5-point scale	
5.4	Different material with additive manufacturing	Yes/No/Maybe	

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4.2.3 Collect the data

Step three of the market analysis was the collection of data once the type of survey is determined. Before collecting the data, the right group of participants and the recruiting method and channel had to be identified. For this survey, people who own a classic car were determined to be the best respondents for this survey. Due to the Corona Pandemic, the recruitment of classic car owners had to be conducted via the internet, since no large events were taking place. Therefore, the recruitment was done on classic car forums. In total, the advertisement for this survey was posted on 21 classic car forums which gave a return of 153 responses over a period of two weeks.

4.2.4 Analyse the data

The analysis of the data was done in phase four. Sarstedt and Mooi (2019) introduced a four-step workflow to analyse data from a survey, as shown in Figure 4.3. This workflow enables a good visibility of the data analysis and provides a repeatability for other researchers.

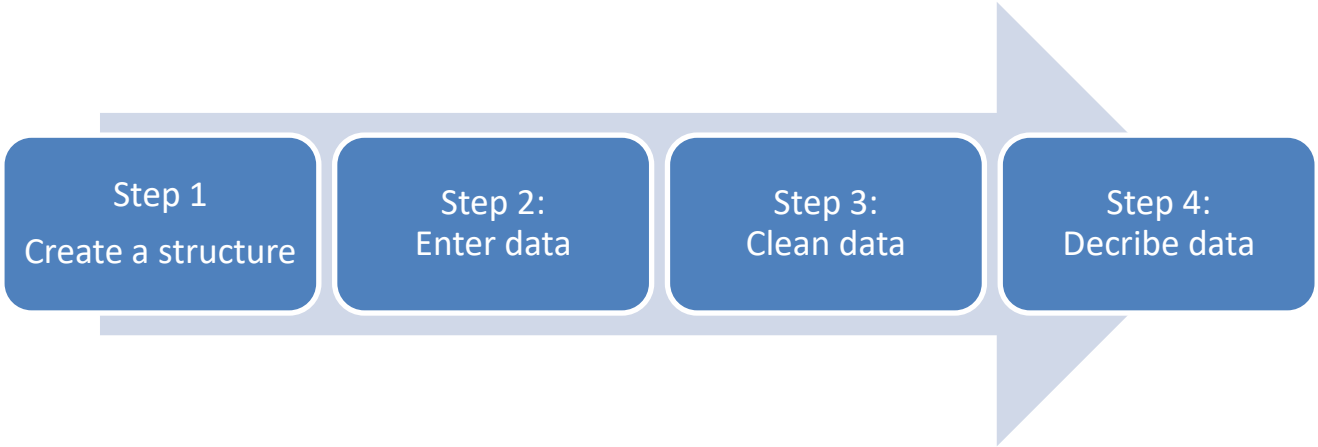

Figure 4.3: The recommended approach for the workflow of survey data, adapted by Sarstedt and Mooi (2019)

The content of each step of the workflow is described as follows:

- Step 1: To create a structure for the analysis of the data, it is recommended to create 4 data files with the original data. One zip folder for safe storage of the original data set, one original data set in the format for further process, and two data sets for revisions while formatting the data (Sarstedt and Mooi, 2019). This structure for the data was adopted for this research.
- Step 2: The data gathered in a survey should be entered into a software program for further analysis. Different software programs from specialized firms are available. The choice of software is done according to the size of the market survey (Sarstedt and Mooi, 2019). The

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software used to design and perform the allowed analysis to export the data was Microsoft Excel. Other software programmes could have been used. However, Excel was determined to have all necessary functions for this analysis. Further, the researchers of this project were already familiar with this software.

- Step 3: Once the data is entered into the software, the data gets cleaned from faults. After cleaning the data of faulty answers, 49 out of the 153 answers were used for the further process. Most answers had to be excluded because of missing data. Other potential faults were also identified, and measures were implemented to avoid these faults. The potential faults when conducting a survey were grouped in 5 different categories as shown in Table 4.2 (Sarstedt and Mooi, 2019).

Table 4.2: Five data fault categories with the potential source and solution used in this research

Data fault categories	***Source for fault***	***Solutions for fault***
Interviewer fraud	Interviewer is influencing the respondents which leads to incorrect results	Self-completion questionnaire lowers the risk of fraud. However, additional measures were set in place: • No introduction given, to not influence personal opinions • Respondents were unknown to the researchers
Suspicious response patterns	Respondents pay less attention to survey	Reparative questions were included to reveal inconsistent answers. Different scales were used in the survey to maintain the focus of the participants. Reversed scaled questions were included to identify straight-lining
Data entry errors	Human fault in processing data	Review the data set by a sampling inspection. Numerical format standards were requested to minimize the risk of data entry errors. Data sets with answers outside the scale were deleted.

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Outliers	Misinterpretation of the questions or entering answers incorrectly	Likert 5-point scale was used to minimize the risk of misinterpretation of the provided answers. The standard deviation analysis was used to identify outliers. Outliers with no clear explanation were deleted.
Missing data	Entire surveys or single questions are not answered by the respondents.	Responses with more than 10% of data missing were deleted.

- Step 4: The choice for a suitable descriptive statistic is mainly influenced by how many variables the statistic should visualize. The analysis of one variable is called "Univariate", and the analysis of two variables "Bivariate" (Sarstedt and Mooi, 2019). A selection of the most popular statistics is given in Figure 4.4. To visualize the results of the online market survey, mainly univariate descriptive statistics were used since each question addresses only one measurement variable. Only the questions regarding customer goals compared two goals pairwise. Therefore, for the analysis of the results of customer goals, bivariate descriptive statistics were used.

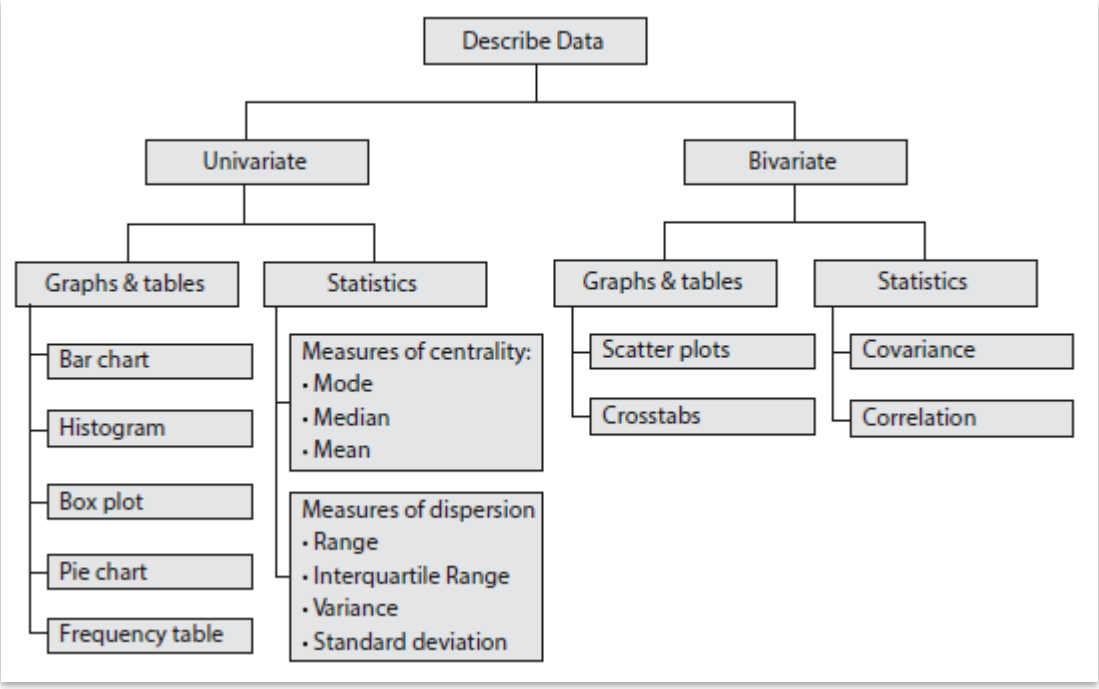

Figure 4.4: The different types of descriptive statistics (Sarstedt and Mooi, 2019)

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4.2.5 Interpret, discuss, and present the findings

"Communicating results is key to any market research project" (Sarstedt and Mooi, 2019). Therefore, the communication of the results to the addressed people was an important step. The process of interpretation started with "Identifying the audience". Depending on the audience`s knowledge, background needs to be provided to explain the market findings. In the case of this research, the audience is, on the one hand, students and lecturers from universities who have an industrial engineering background. On the other hand, people who are interested in classic cars or additive manufacturing might read this report. Therefore, the results were presented in a way that people without classic car or additive manufacturing knowledge understand the findings.

Sarstedt and Mooi (2019) highlights that the summarization and interpretation of the data should be addressing the research objectives. Furthermore, the presented information should be relevant for answering the research questions. The researcher should present the findings in an unbiased and impersonal manner, and personal conclusions and interpretations must be recognizable as such (Sarstedt and Mooi, 2019). The objectives of this research stated that a database of classic car spare parts must be created to rank the parts according to their potential for the use of additive manufacturing. The outcome of the ranking was used to answer the research question. To meet the other guidelines from literature stated above, the most relevant results of the survey are presented in the following section. For the presentation of the survey results, which were in text format, the "word cloud" format was chosen. A word cloud is a type of data visualization for textual answers. The bigger and bolder a word appears in the word cloud, the more frequent a word is used in a text.

In the market survey, the respondents had to choose if the respondent owns more than one classic car. The selected car was questioned by its make and model. The responses were grouped into one text and visualized in a word cloud as shown in Figure 4.5. Results show that most classic cars entered the survey were from England. The brands "Triumph", "MG" and "Austin" are written in the largest letters and are therefore answered the most.

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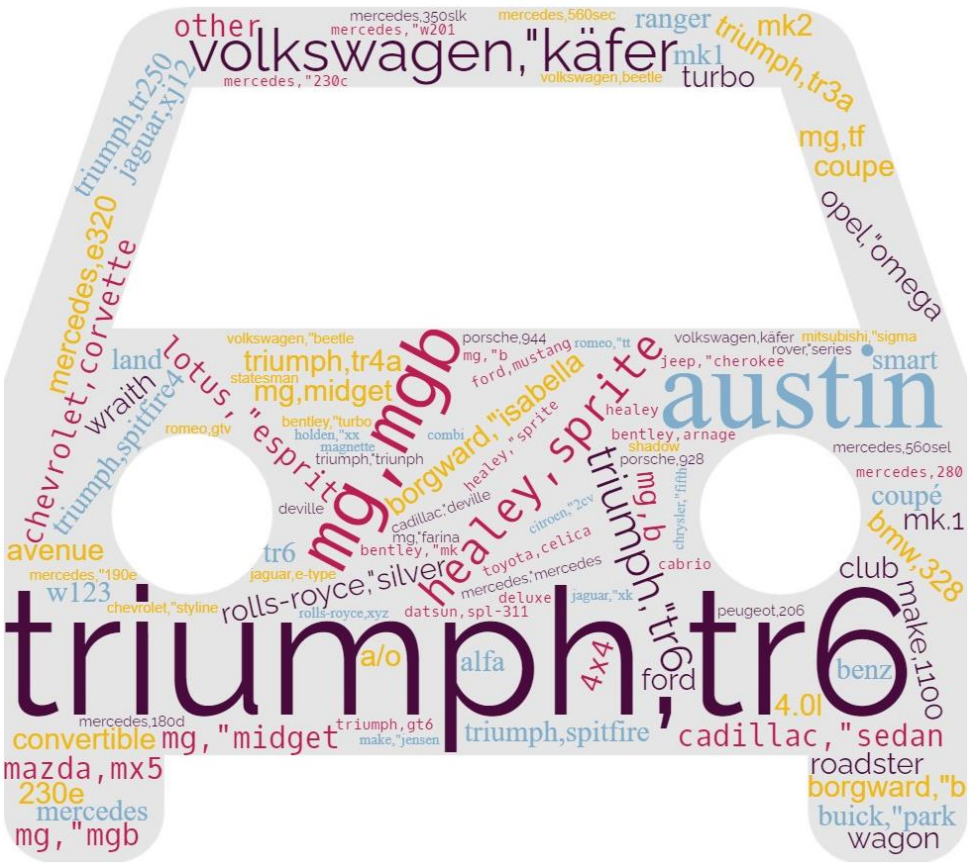

Figure 4.5: A word cloud of the responses from the market survey regarding the make and model

Further in the survey, the participants were asked to enter a spare part, of the selected classic car, by which they experienced unsatisfied demand. First, the participant was asked to select the assembly group of the part. Secondly, the participant was asked to write a descriptive text of the part. The answers regarding these two questions are visualized in a second word cloud as shown in Figure 4.6. The word cloud highlighted especially the words “Dashboard”, “Body”, “Panels” and “Instruments”.

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Figure 4.6: A word cloud of the responses from the market survey regarding the assembly group and part names

The selected spare part was further considered in the survey, by investigating all its characteristics. The first characteristic investigated was the materials the part is made of. Participants were asked to select the material from the given answers. The possibility to select multiple materials was given to allow the entering of parts of assemblies with multiple materials. The results of Figure 4.7 showed that most parts are made from steel, plastic, or aluminium.

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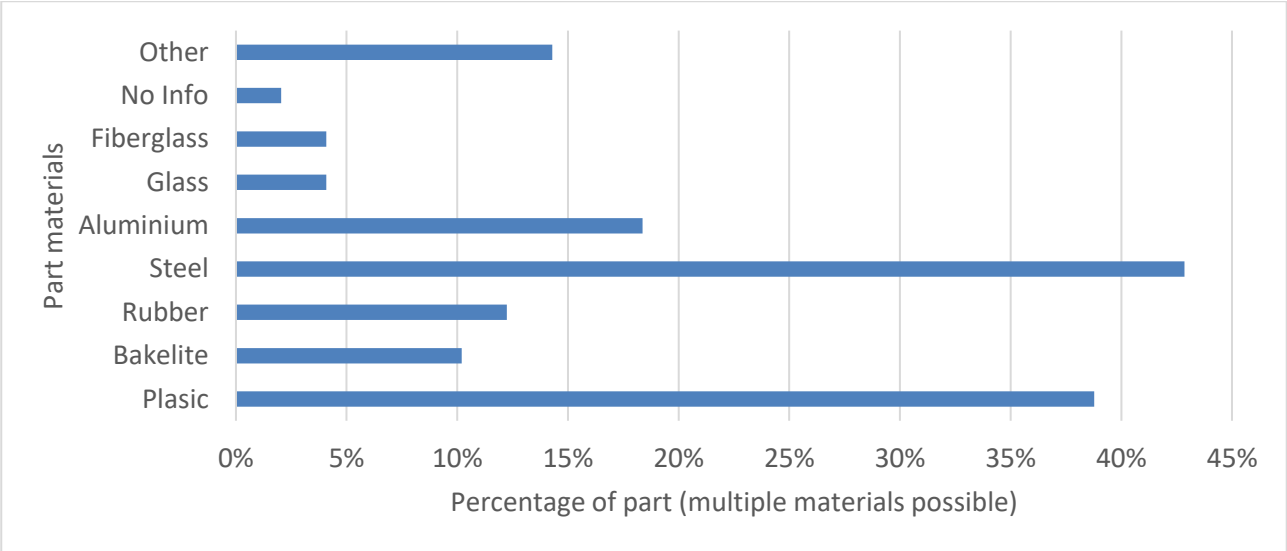

Figure 4.7: Results from the market survey regarding the part materials and its response frequency

The next spare part characteristic considered, was the availability of the part. A single question was asked on the availability of the spare part through both the dependent and the independent supply chain channel. Figure 4.8 shows that spare parts are in general more available through the independent supply chain channel (32% availability) than through the dependent supply chain channel (18%). If the spare part was available through one or both channels, the respondent was asked to select from the given answers why his demand is unsatisfied. If the part was available through the dependent channel, customers were mainly unsatisfied through exorbitant spare part cost, as shown in Figure 4.8. The reasons for dissatisfaction about parts from the independent channel were diverse. In terms of the replica part, “Poor quality” (47%), is “not true to original” (37%) or has” infrequent availability” (32%) were the reasons which were most often selected.

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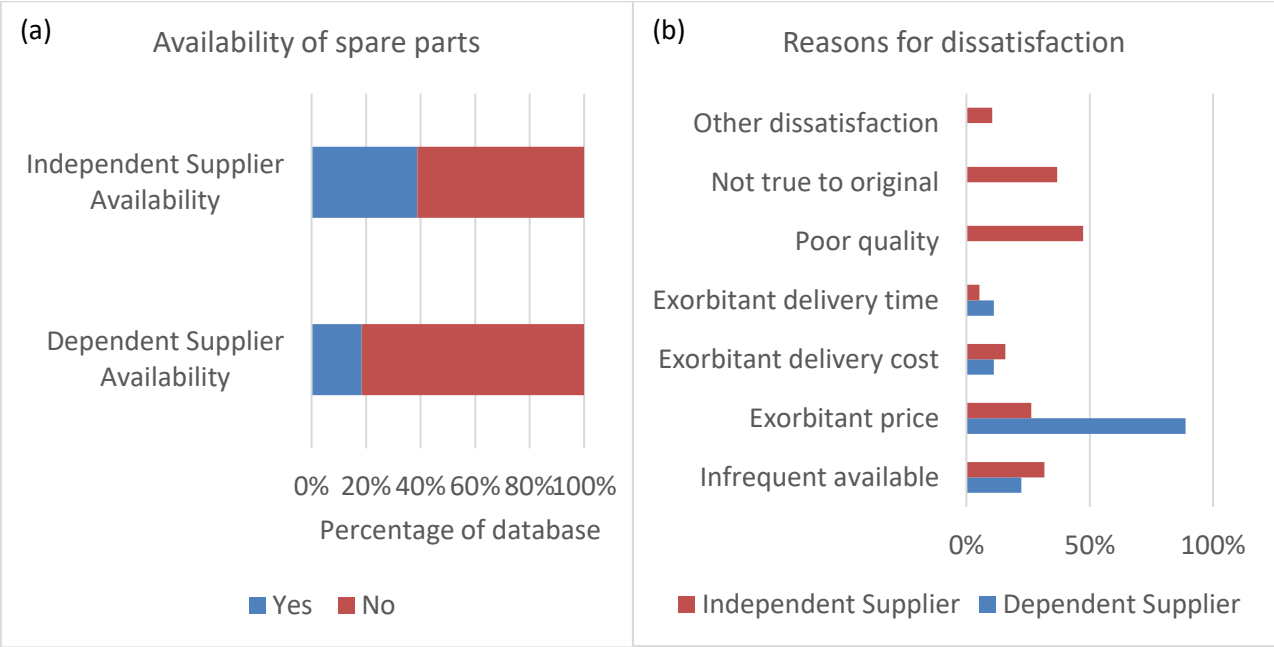

Figure 4.8(a) and (b): (a) Availability of spare parts at brand dependent and independent spare part suppliers; (b) Reasons for dissatisfaction of brand dependent or independent spare part suppliers

In the next step, the focus was shifted from the characteristics of a selected spare part to the general goals of customers when purchasing spare parts. Participants were asked to indicate their preferences by comparing two goals. The answers were inserted into the survey by sliding a cursor on a 100-point scale. Figure 4.9 shows that participants rate the goal "Low part price" with a level of 58 higher than the goal "Short delivery time" with a level of 42. A similar result was observed with the comparison of the goals "Low delivery cost" and "Short delivery time". With a balance of 55 to 45, "Low delivery cost" is rated higher than a "Short delivery time". A clear result was observed in the last comparison. With a balance of 82 to 18, "High quality" was preferred over "Low part prices".

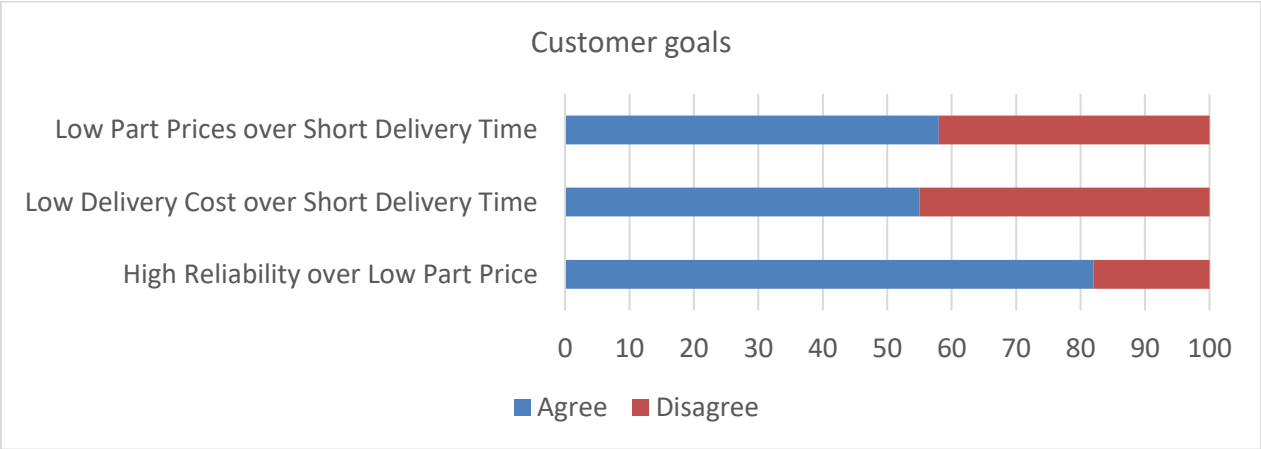

Figure 4.9: Answers regarding three comparisons of customer goals

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Lastly, questions facing additive manufacturing were inserted into the survey. To interpret the responses correctly, the participants were asked first to select their level of knowledge. The average respondent answered that his "level of knowledge on AM" is beneath the expected average knowledge of the population, as shown in Figure 4.10. Further, the average participant responded that his trust in additive manufacturing is high and that he is willing to purchase these parts. When purchasing additive manufactured parts, 94% of the respondents would accept a different material than used for the original part.

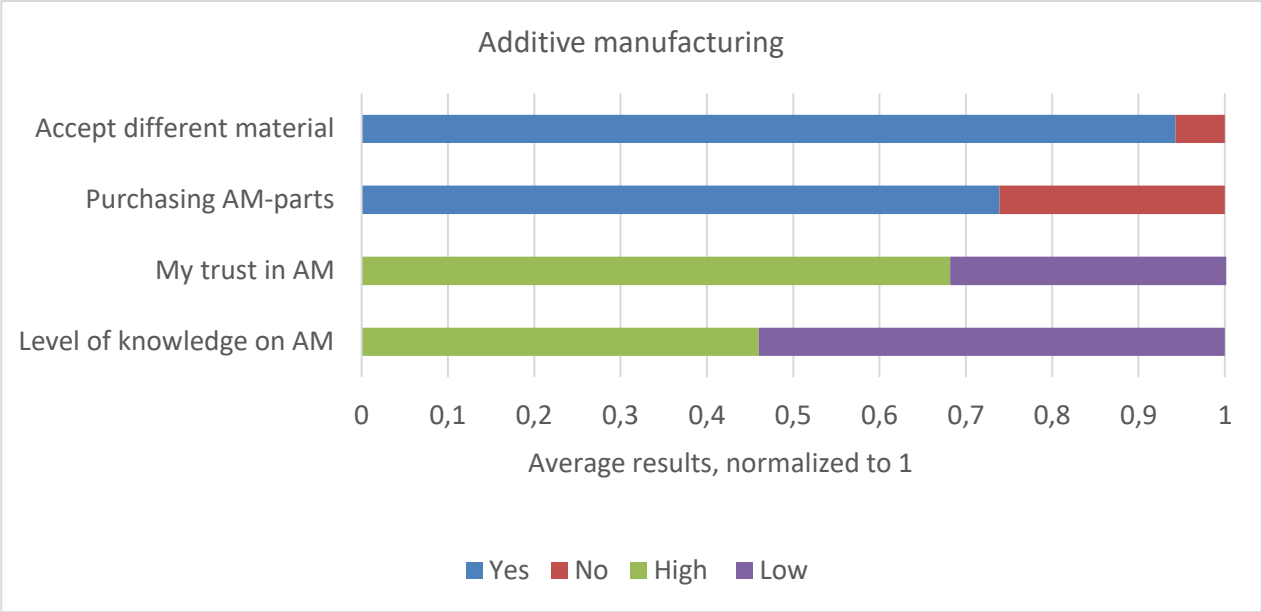

Figure 4.10: Responses of participants on their attitude towards additive manufacturing for spare parts

4.2.6 Follow up

At the end of a market survey, which involves participants to collect primary data, the researcher has to thank the participants and explain what will happen with the data (Bryman, 2015). In this market survey, the advertisement text was used to inform the participants about the reasoning of this survey and the further process of the data. The advertisement included that this research is conducted during a master's research project and is used to identify potential applications for additive manufacturing. After the survey, the participants were thanked for taking part in the survey. To increase the number of participants and to add a personal benefit for participants, a lucky draw was set up. A participant enters the lucky draw if his survey response was included into the ranking. For example, if more than 10% of the data was missing the participants were excluded from the lucky draw. These rules were stated in the advertisement of the survey. Furthermore, the participants had to enter their Email

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address to correspond with the results of the lucky draw. The prize for the winner of the lucky draw was a small-scale model of the winner's classic car, produced with additive manufacturing. Figure 4.11 shows the customized prize, a small scale-model of a Jeep Cherokee XJ from 1994.

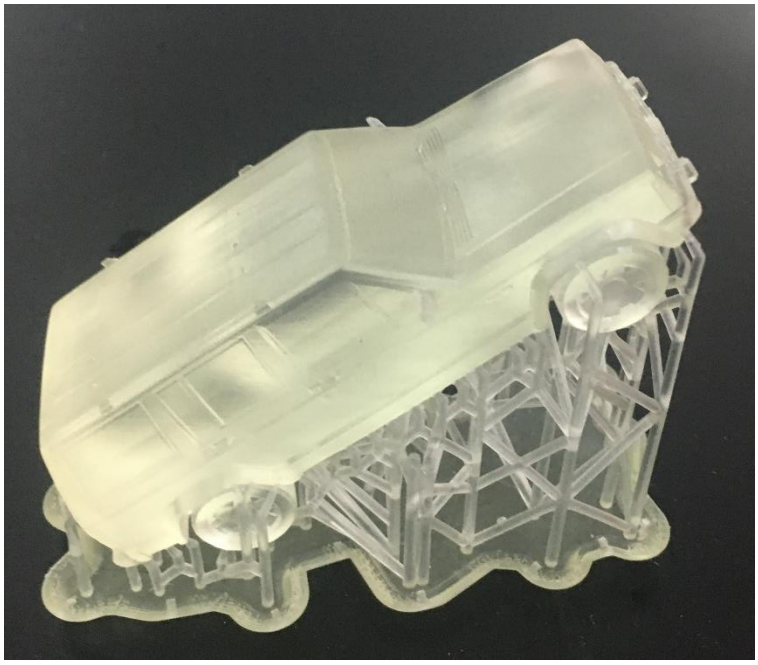

Figure 4.11: Capture of the price for the winner of the lucky draw

4.3 Ranking Method

In Chapter 3.3 the Ranking Methodology of Knofius, van der Heijden and Zijm (2016) was presented and the adjustments which had to be made were highlighted. In this chapter, the process steps 2 (Identify spare part attributes), 3 (Link attributes to the potential for additive manufacturing) and 4 (Rank spare parts according to attributes) of the modified methodology were conducted. Figure 4.12 reminds about the tree step ranking processes and provides a guideline for Chapters 4.3.1 to 4.3.3.

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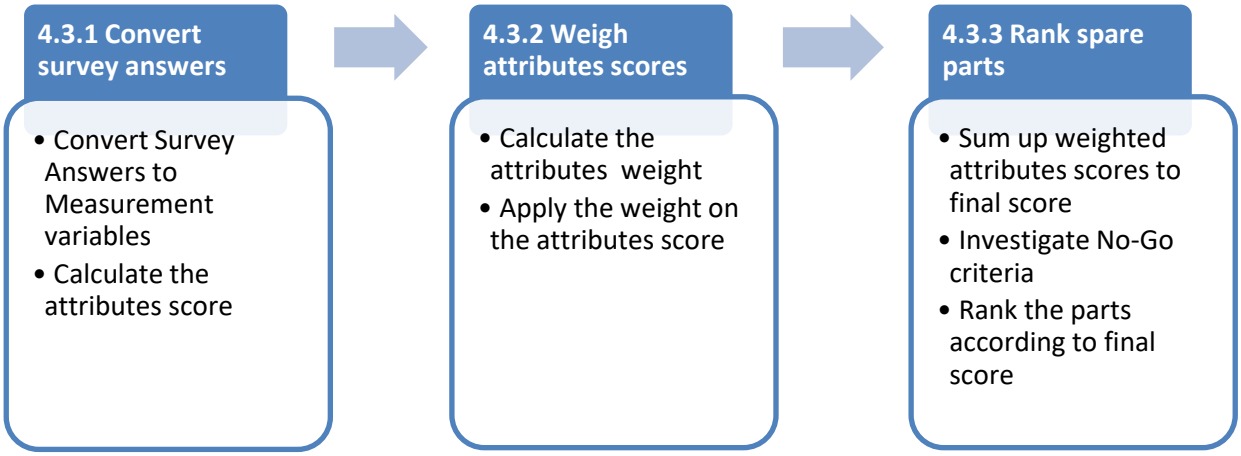

Figure 4.12: Main actions of the three-step ranking process

4.3.1 Convert survey answers

The 5-point Likert scale was identified in Chapter 3.3.2 as the best suitable scale for the survey responses. To simplify the ranking process, the 5-point scale was used as the standard unit. All responses which were collected in a 5-point scale had to be standardised according to the identified potential for additive manufacturing from Chapter 3.3. That means that the answer with the highest potential for additive manufacturing must get the highest score - in this case, the value 5.

Measurement variables which were not in the standard unit had to be converted. Table 4.3 shows the method used to convert the relevant answers for the relevant measurement variables for this process step into the 5-point scale. The reasoning for the value is explained, again, in Chapter 3.3.2.

Table 4.3: Listing of the measurement variables and the underlying formula for the conversion to a 5-point scale

Num.	*Measurement variables*	*Scale*	*Conversion*
1	Personal information		
1.1	Participant's location	Select answer	Value 1 = Participant's location is a county with a car manufacturers head quarter Value 2 = Participant's location is a neighbouring county with a car manufacturers head quarter. Value 4 = All other participants' locations

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2	Ownership information		
2.3	Model year	Select answer	Calculation of 20th, 40th, 60th and 80th percentile of all responses. The percentiles set the border for 5 groups of equal size. Value 5: 0 - 1963 Value 4: 1964 - 1967 Value 3: 1967 - 1974 Value 2: 1975- 1988 Value 1: 1989 - today
3	Spare part – unsatisfied demand		
3.5	Available at dependent supplier	Yes/No	Value 5: No, not available Value 1 Yes, available
3.7	Available at independent supplier	Yes/No	Value 5: No, not available Value 1: Yes, available
5	Additive manufacturing		
5.4	Different material with additive manufacturing	Yes/No/Maybe	Value 5: Yes Value 3: Maybe Value 1: No

To get the result of process step a), e.g., the attributes score, the average of measurement variables values were calculated. This calculation was only carried out if more than one measurement variable contributes towards the attributes score.

4.3.2 Weight attributes score

In Chapter 3.3, four improvement potentials using additive manufacturing were identified, “Reduce cost”, “Reduce downtime”, “Additional customers satisfaction” and “Supply chain flexibility”. The customer goals are based on these improvement potentials of additive manufacturing. Asking customers for their goals with regards to additive manufacturing was limited by their level of knowledge on additive manufacturing. In addition, the collection of customer goals was limited by the capabilities of a web-based survey. The survey output and the calculation of customer goals are visualised in Figure 4.13. Three comparisons were gathered from the survey. However, only two out of three comparisons were used to avoid a statistical overrepresentation of two improvement potentials. The results from the survey were averaged, resulting in the customer goal “Reduce

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Downtime" being rated at 63,5% and "Reduce Price" being rated at 36,5%. The underlying equation adds the two scores of the comparison and divides this intermediate result by two (e.g. (18+55)/2=36,5).

It was determined that customers cannot decide between the other customer goals "Supply chain flexibility" and "Additional Customers' Satisfaction". Therefore, the weight for these customer goals was set at a fixed value. Based on the overall number of improvement potentials (6) the customer goals "Additional customers' satisfaction" and "Supply chain flexibility" received each the set value of $\frac{1}{6}$ which rounded to 17%. The remaining $\frac{4}{6}$ was divided according to the "63,5 to 36,5" ratio calculated from the survey data. This results in a weight of 24% allocated to the customer goal "Reduce cost" and a weight of 42% for the customer goal "Reduce downtime".

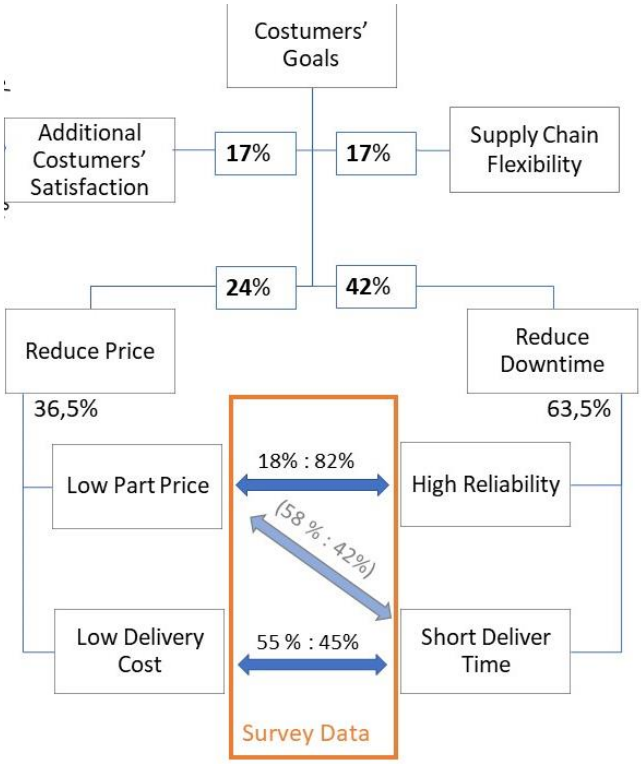

Figure 4.13: Distribution basis for the weight of customer goals

The weights of customer goals were identified. However, these weights had to be linked to the spare part attributes. The calculation of the weight of the spare part attribute was based on the relation between the attribute and an improvement potential using additive manufacturing. If a spare part attribute indicated an improvement potential utilising additive manufacturing, as shown in Table 3.2 (Page 94), the value of the associated customer goal was added to the subtotal score of the spare part

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attribute, as shown in Table 4.4. If spare part attributes showed an improvement to both subcategories of a customer goal, then the weight was added only once. The subtotals of all spare part attributes were summed, and their score was normalized to a total of 100%, which led to the final calculated weight.

For a detailed explanation of this scoring method an example is given. A low demand rate for a spare part is associated with each subcategory of both improvement potentials “Reduce cost” and “Reduce Downtime”. In addition, the supply chain flexibility can be increased for a spare part with low demand when utilising additive manufacturing. Table 3.2 visualizes these mentioned connections. The connections are transferred into Table 4.4 in which the improvement potentials using additive manufacturing are now called “Customers’ goals for Improvement”, but still represent the same improvement potential. In the example of the “demand rate” which is connected to three improvement potentials, the three weights of customers’ goals are summed (e.g., 24%+ 42% + 17% = 83%). The subtotal of 83% is set in relation to the other spare part attributes’ subtotals and normalized to 100% (e.g., 83% / 451% ≈ 18,5%). The calculated weight is rounded to a scale 0,5% as a compromise between spurious accuracy and rounding errors, and to bring the final score to 100%.

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Table 4.4: Calculating the individual weights for the spare part attributes from the customer goals

		Customers' goals				***Calculated weight*** ***Normalized to 100%***	***Sub-total weight***
		Reduce cost	Reduce downtime	Additional customer's satisfaction	Increase supply chain flexibility		
Weight of customers' goals		24%	42%	17%	17%		
Spare part attributes	Demand rate	x	x		x	18,5%	83%
	Availability	x	x		x	18,5%	83%
	Delivery time discrepancy	x	x		x	18,5%	83%
	Replacement urgency	x	x			14,5%	68%
	Customers order cost	x				5,5%	24%
	Innovation potential		x	x		13%	59%
	Individualization potential			x		4%	17%
	Openness for AM			x	x	7,5%	34%
	Mechanical stress	Go/No-Go					
	Material	Go/No-Go					
	Size	Go/No-Go					
						100%	451%

4.3.3 Rank spare parts

By summing up all weighted attributes, the final score was calculated. Because the weight attached to the attribute scores was normalized to 100%, all scores were still on the unified scale reaching from one to five. A score of one represents the lowest, and a score of five the highest potential for additive manufacturing. The range was extended with the possible score of zero. A score of zero can be scored if a part did not meet the requirements of the Go/No-Go criteria. In Chapter 3.3 the criteria "Mechanical stress", "Size" and "Material" were identified. All 49 parts were reviewed regarding these criteria.

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The level of stress on all parts was examined and none of the parts were clearly unsuitable for additive manufacturing. Through the ranking process, this Go/No-Go criteria was identified to not have firm boundaries. This criterion has to be reviewed in the context of all spare part attributes. Three parts were identified as not feasible because of its size. An engine block, a rear axle and a rear bumper were too large for usual additive manufacturing machines. The option to divide the parts for the production process and assemble them afterwards was considered for these parts. However, the engine block and the rear axle are also both exposed to high levels of mechanical stress. Underlying these two constraints, the parts were excluded from the ranking. The rear bumper was excluded because its size exceeds the capacities of usual additive manufacturing machines multiple times.

Lastly, one part was considered to be unfeasible for the additive manufacturing process not only due to its material, but rather due to a combination of No-Go criteria. The rear window, made from glass, could be produced by using additive manufacturing, however, the size in combination with the expectations on its clarity make this case highly uneconomic. Therefore, this part was excluded from the ranking. This decision was supported by the fact that the rear window also ended up on the last place of the ranking due to its low scores on other attributes. With including the Go/No-Go criteria into the ranking process, all attributes and weights were considered. The 45 remaining parts were ranked according to their final score. The results are presented in the following chapter.

4.3.4 Results

The scores of the remaining parts raged form the lowest score of 2.2 to the highest score of 4.1. The detailed scores of some selected parts are visualized in Table 4.5. The two highest and the two lowest rated parts were selected. Further, four randomly selected parts were used for visualizing the results. The attribute scores and the weight attributes scores of a spare part are shown below. Summing up the weighted attributes scores resulted in the final weighted score.

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Table 4.5: Examples of the calculation of the final score

		Spare part attributes																
		Demand rate		**Availability**		**Delivery time discrepancy**		**Replacement urgency**		**Customers order cost**		**Innovation potential**		**Individualiza-tion potential**		**Openness for AM**		
Make & model	***Part description***	Attributes score	Weighted 18.5%	Attributes score	Weighted 18.5%	Attributes score	Weighted 18.5%	Attributes score	Weighted 14.5%	Attributes score	Weighted 5.5%	Attributes score	Weighted 13%	Attributes score	Weighted 4%	Attributes score	Weighted 7.5%	***Final weighted score***
Mazda MX5	**Alternator**	1	0,19	1,3	0,25	3,5	0,65	4	0,58	1	0,06	2	0,26	1	0,04	3,0	0,23	**2,2**
MG MGB	**Dash Switch**	2,5	0,46	2,7	0,49	3	0,56	2	0,29	1	0,06	1	0,13	3	0,12	3,3	0,24	**2,3**
Triumph TR6	**Trailing arm**	2	0,37	4,0	0,74	3,5	0,65	5	0,73	1	0,06	1	0,13	1	0,04	3,5	0,26	**3,0**
Jaguar E-type	**Windscreen demister vents**	4	0,74	2,7	0,49	4	0,74	3	0,44	1	0,06	2	0,26	1	0,04	3,0	0,23	**3,0**
Triumph TR4a	**Exhaust manifold**	3	0,56	4,0	0,74	3,5	0,65	2	0,29	1	0,06	4	0,52	3	0,12	4,3	0,32	**3,2**
Mercedes 280	**Badges**	2	0,37	4,7	0,86	4,5	0,83	3	0,44	4	0,22	3	0,39	4	0,16	3,5	0,26	**3,5**
Jaguar XK 150	**Dashboard Switches**	4,5	0,83	4,3	0,80	4	0,74	3	0,44	4	0,22	4	0,52	2	0,08	3,8	0,28	**3,9**
BMW 328	**Brake shoes**	5	0,93	4,3	0,80	4	0,74	4	0,58	1	0,06	4	0,52	5	0,20	3,8	0,28	**4,1**

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4.3.5 Statistical analysis

For the scoring method a statistical analysis was performed to identify imbalances. Through the ranking process, especially the manual steps like converting survey answers into measurement variables and converting scores to the unified 5-point scale, imbalances might have influenced the final score. Furthermore, a ranking based on 49 survey answers is not a significant statistical sample. Therefore, the statistical analysis could have shown imbalances or outliers.

Both the median and the mean are a measure of the central tendency. However, outliers may have less of an effect on the median than on the mean. For symmetric data, the mean and median are similar. The comparison of the Median and the Mean of a weighted attributes score is visualized in Table 4.6. A high deviation of the median from the mean was observed with the attribute "Customer's order cost". The reason for this deviation is the manual conversion of the survey results into a measurement variable. Most survey participants live in a country where a car manufacturer has its headquarters, like Germany or the United States. These countries received a measurement variable value of one. However, many participants of the survey were from South Africa due to the location of this research. South Africa is not a country with a headquarters of a major car manufacturer and receives, therefore, a value of 4. This imbalance was accepted since this attribute only contributed 3% to the final score. The imbalance with the attribute "Individualization Potential" could be explained by the fact that many participants did not see an individualization potential of their spare part while some others see a high potential. However, this attribute also contributed only 3% towards the final score.

The relative standard deviation is used to determine the spread of the data from the mean. The high spread of the attributes "Individualization Potential" and "Customer's order cost" was already explained in Chapter 4.3. It can be observed that the attribute "Demand Rate" had a high relative standard deviation while having a symmetric set of data. A similar observation could be made regarding the final score. The median and mean had the same value, but a relative standard deviation of 30% was achieved.

Last, Table 4.6 shows that some attributes had a higher or lower impact on the final score than the addressed weight. It turns out that the attribute "Delivery time discrepancy" had a higher proportion on the final score than the addressed weight. This was caused by a skewed distribution. Most

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participants have answered that they experienced a high delivery time for spare parts while having the expectations of low delivery times. Therefore, most spare parts had a score of four or five on this attribute. Overall, none of the statistical measures showed a critical value which would have required adjustments to the ranking process.

Table 4.6: Statistical analysis of the attributed scores

	Demand rate	*Availability*	*Delivery time discrepancy*	*Replacement urgency*	*Customers order cost*	*Innovation Potential*	*Individualiza-tion potential*	*Openness for AM*	*Final score*
Median	0.46	0.68	0.74	0.44	0.06	0.39	0.08	0.26	3.1
Mean	0.45	0.63	0.71	0.46	0.08	0.37	0.09	0.26	3.1
Deviation of median and mean	3%	7%	5%	6%	34%	5%	15%	0%	0%
Relative standard deviation	39%	28%	12%	28%	66%	32%	52%	14%	30%
Proportion of final score	14%	20%	23%	15%	3%	12%	3%	9%	100%
Attributes weight	18.5%	18.5%	18.5%	14.5%	5.5%	13%	4%	7.5%	100%

4.4 **Delphi-survey**

Although the statistical analysis of the attributes and final score did not indicate major signs of inaccuracy, all decisions made throughout the ranking process must be validated. The method chosen for the validation is the Delphi survey, as already mentioned in Chapter 3.3. To provide more of a background about the Delphi method, the possible applications are presented, the process steps are explained, and the advantages and disadvantages are highlighted. The information for this background of knowledge were sourced from two journal articles. The articles from Hasson, Keeney and McKenna (2000) and Mullen (2003) were chosen because their level of detail on the Delphi method suited best for the utilization as a validation method for the spare part ranking framework. Furthermore, both articles have in common that they are applicable to various areas and that they are relatively recently published in comparison to Linstone and Turoff (1975), one of the most cited references regarding the Delphi method.

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In this chapter, the reasons for choosing the Delphi survey as a validation are provided. Further, the process chain of the survey is explained and the decision variables in that process are highlighted. Some decisions were made to successfully apply the Delphi survey on this research project. For the decisions taken, arguments are given.

4.4.1 Introduction

"Delphi may be characterized as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem" (Linstone and Turoff, 1975). The complex problem of this research project was characterized by the need for a validation of the cross-functional ranking method. The goal of the validation problem was to gain consent about the ranking of the database's spare part assortment. Hasson, Keeney and McKenna (2000) recommend the Delphi survey for problem solving objectives which "explore underlying assumptions leading to different judgements" and "correlate informed judgement on a topic spanning a wide range of disciplines". Therefore, the Delphi survey was identified as the ideal survey method for the validation of the ranking method.

4.4.2 The sample

For the selection of an appropriate sample of experts for the survey, Hasson, Keeney and McKenna (2000) recommends sampling techniques based on the knowledge of the experts. Mullen (2003) highlights that heterogeneity of the participants assures validity of the results and can improve the results by not overlooking obvious issues. A heterogeneous mix of participants may also include a random sample as an unusual representative (Mullen, 2003). A heterogeneous mix of participants was also the basis of this research. Participants from the areas of car manufacturing, additive manufacturing and classic cars were invited as feasible for this survey. Furthermore, the goal was to follow the recommendation of including one random sample. It turned out that seven out of nine invited experts from the relevant industries participated in all three rounds of the survey. The random sample, chosen from the previously conducted market survey, did not accept the invitation.

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4.4.3 Survey process and results

"The Delphi is a group facilitation technique that seeks to obtain consensus on the opinions of experts through a series of structured questionnaires" (Hasson, Keeney and McKenna, 2000). Most Delphi surveys use self-completion questionnaires, of which most are electronic format. Answers in the Delphi survey are usually given on number scale format, reaching from three-point format to 100-point format. In this survey, self-completion questionnaires in electronic format were used to conduct the Delphi survey. The same 5-point Likert scale from the market survey was used, whenever possible, in the Delphi survey, so that the results stay comparable.

The participants of the Delphi survey stay usually anonymous to other participants which can be a strength and a weakness of this method at the same time. Anonymity eliminates the group related pressures and creates freedom in sharing personal opinions. In contrast, anonymity lowers accountability for responses and might decrease the extent of exploratory thinking (Hasson, Keeney and McKenna, 2000; Mullen, 2003). In this survey, a balance of both approaches was used. The participants had to stay anonymous to adhere to the consent form. However, the participants got codes according to their areas of work and their job titles. With this solution, the participants did not have any group pressure, but still knew from whom the answers came.

After each questionnaire, also referred to as round, the responses were analysed, and feedback was provided to the experts through the next questionnaire. The feedback informed the experts about the status of discussion and ensured that all experts have the same knowledge.

This repetitive process can be continued until either a consent is achieved, or the time limit is reached, however usually two to four rounds are usual (Hasson, Keeney and McKenna, 2000; Mullen, 2003). In this research, the experts were informed that the total survey will take 30 minutes. This time carpathite was identified as the ideal compromise between having enough time to collect information and having a deterrent effect of asking for too much time from the experts. With the given time constraints, three rounds of ten minutes each were selected. Since each round included feedback and a survey, the 10 minutes were divided. To minimise the time consumption of the feedback, the video format with the presentation of the results was identified as a time saving solution.

The approach of the Delphi survey was to let the experts create their own ranking, while still using the structure of the ranking method of this research. Figure 4.14 illustrates all three rounds of this

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survey. Round one consisted of gathering and weighing measurement variables, which influence the potential of spare parts for additive manufacturing. In round two the measurement variables were combined to spare part attributes. The participants scored the spare parts from the database according to the attributes. For the third round, the ranking of the parts according to the attributes scores was calculated. The results were presented, and the experts had to indicate if they agree with the results. In the further paragraphs, the detailed process of the Delphi survey is explained.

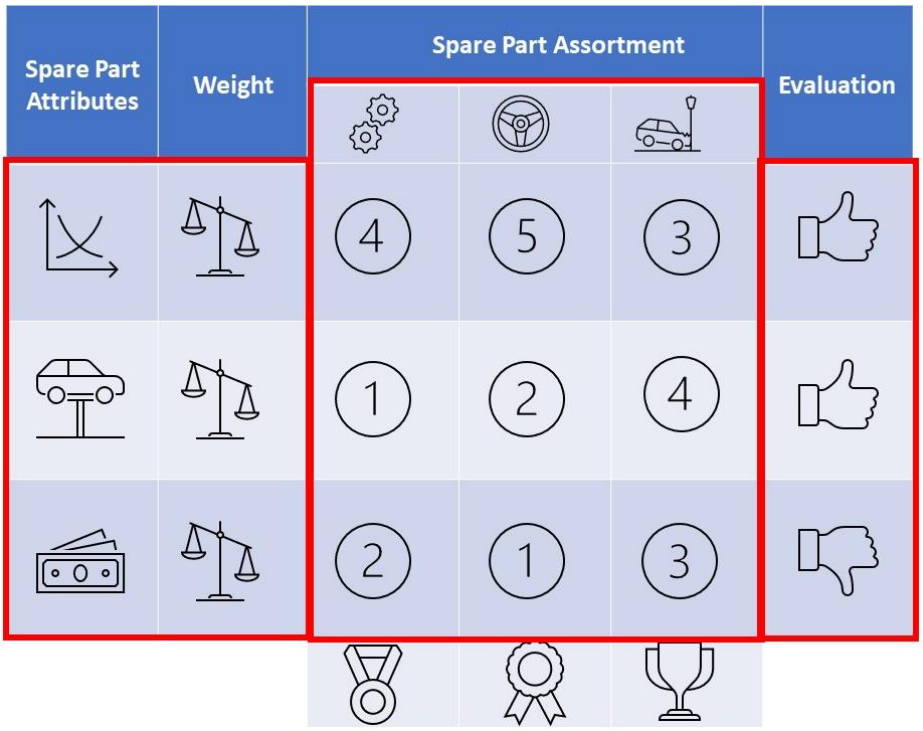

Figure 4.14: The three rounds of the Delphi survey: First, the identification of spare parts attributes and its weights. Second, the scoring of parts and last, the evaluation of the results.

Round 1

Before starting the survey, participants should be provided with important information like the process of the survey, the estimated time frame of the survey and the aim of the study. By providing a background about the survey a relationship is created with the participants which should increase the probability that participants complete all rounds (Hasson, Keeney and McKenna, 2000). Since no feedback could be given in the first round, the time slot was used to inform the participants about the process and background of this Delphi survey (Link to the introduction video: https://www.youtube.com/watch?v=Nc9WI-yvIlk&ab_channel=Classic_Revolution).

For the first round of the survey, open-ended questions can be used to generate ideas without limiting the answers. On the other hand, open-ended questions are producing large amounts of data. Therefore,

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many researchers have limited the number of responses. If a literature review was conceived prior to the survey then this information could also be used in the design process of the first questionnaire (Mullen, 2003). However, it must be recognized that providing information before a survey "could bias the responses or limit the available options" (Hasson, Keeney and McKenna, 2000).

In round one, the experts were asked to identify relevant measurement variables to analyse the potential of a spare part for additive manufacturing. This could be done either by selecting from the given answers, which are the measurement variables from the ranking, or the participants could enter their own variables in the text boxes. This approach therefore included information from the previously conducted literature review with limited risk for biassing the respondents. The open-ended questions provided the respondents with freedom to answer without limitations.

After selecting or inserting the relevant variables, the participant had to weigh these variables according to their importance. The participants had to select the level of importance on a 100-point scale. However, the level of importance was only used for the when summarizing the measurement variables to spare part attributes. For example, if a participant indicated a high level of importance for a variable, and if the variable was mentioned by other participants as well, then the variable was converted to a single attribute. If a variable had a low level of importance and was only mentioned by one participant, then it was grouped with other variables to one attribute. This grouping process simplified the further ranking process and kept the process visible for the participants. Table 4.7 shows all mentioned measurement variables and how they were grouped to spare part attributes.

Table 4.7: Measurement variables identified by the experts of the Delphi survey

Spare part attributes	***Measurement variables***
Demand rate	Demand rate
Current part cost	Part price; Vehicle's value
Remanufacturing cost and time	Remanufacturing cost; Remanufacturing time
Storage suitability	Warehousing cost; Obsolescence risk
Level of stress	Mechanical-, thermal-, chemical- requirements;
Suitability for additive manufacturing	Material availability; surface; colour; size; geometry

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Round 2

The second round of the Delphi survey started with the feedback video of the responses from round one (Link to the feedback video: https://www.youtube.com/watch?v=dNF4qjk5-Pg&ab_channel=Classic_Revolution). The video visualized all variables answered in the survey. Furthermore, the reasoning and process grouping the variables into attributes was explained. Lastly, an introduction for the second questionnaire was given.

For the questionnaire of round two, six spare parts were selected to represent the database in the validation process. The parts were chosen to have a wide variety of part characteristics unified in the validation. The selected parts and the main characteristics of these parts are stated in Table 4.8.

Table 4.8: Selected spare parts and its characteristics, selected for the Delphi survey

Make & model	***Part description***	***Main characteristics***
Triumph TR6	Trailing arm	Large size metal part; High mechanical stress
Jaguar E-type	Windscreen demister vents	Small size metal part; Low level of stress
Triumph TR4a	Exhaust manifold	Large size metal part; High thermal stress
Mercedes 280	Badges	Small size metal or plastic part; No mechanical stress
Jaguar XK 150	Dashboard switches	Small size plastic part, Low level of stress
BMW 328	Brake shoes	Medium size metal part; High thermal stress

The experts were then asked to score each spare part according to the attributes. The scoring was done by answering in the 5-point scale format. The result was a database of seven responses on six spare parts with six attributes. To calculate the final experts scores of the spare parts, the scores on the attributes of a spare part were averaged. The results of the experts' scores are shown in Table 4.9.

By comparing the scores from the experts with the scores from the ranking method, only slight differences can be observed. The most dominant difference is that the brake shoes scored highest in the ranking method but came second last in the experts ranking. Except for the brake shoes, the parts with the lowest score (3.0) from the ranking scored also the lowest in the experts ranking. Furthermore, the parts with higher scores (3.5, 3.9) in the ranking method scored also highest in the experts ranking (3.50, 3.61).

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Table 4.9: Comparison of the experts score and the score of the ranking method on the selected spare parts

Make and model - Spare part	*Expert's score*	*Ranking method score*
Triumph TR6 - Trailing arm	3.27	3.0
BMW 328 - Brake shoes	3.31	4.1
Jaguar E-type - Windscreen demister vents	3.40	3.0
Triumph TR4a - Exhaust manifold	3,42	3.2
Jaguar XK 150 - Dashboard Switches	3.50	3.9
Mercedes 280 - Badges	3.61	3.5

Round 3

For the feedback from round 2 the average scores for the attributes of a spare part were presented (Link to the feedback video: https://www.youtube.com/watch?v=kX7mnUFsVOY&ab_channel=Classic_Revolution). An example is shown in Figure 4.15. For each spare part the place, total score and the scores of the attributes were presented. The most relevant attribute scores were highlighted. In addition, for all attributes, the minimum and maximum scores of the other spare parts were indicated with arrows.

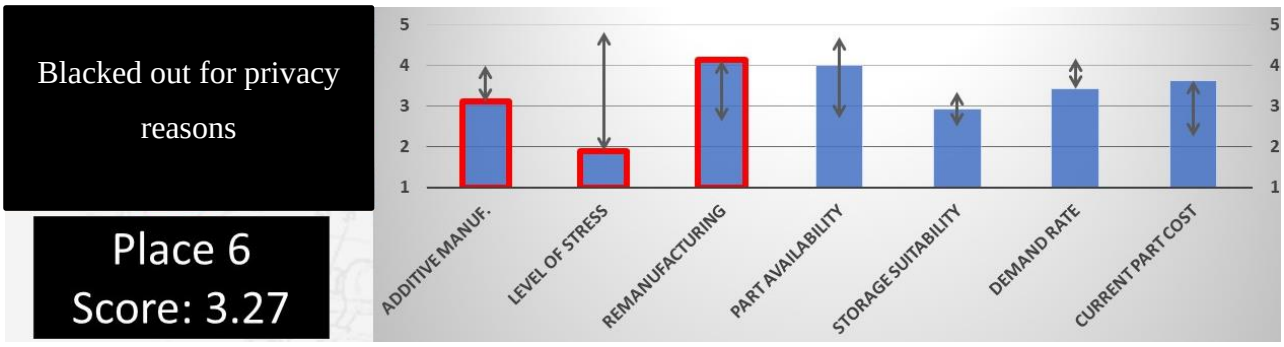

Figure 4.15: Example of visualized feedback presented to the experts of the Delphi survey

In the questionnaire of round three, the participants were asked if they agree with the place of the ranking and with the scores of all attributes. As Table 4.10 shows, more than two thirds agreed with the places and the scores of all attributes. A comment box was added to each spare part in the survey for the participants to argue for their answers. Table 4.10 shows the most highlights of the comments. From these comments, improvements on the ranking can be derived.

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Two comments suggested that place number 4 "Windshield demister vents" and place number 3 "Exhaust manifold" should swap places. This request could be supported by the fact that the two parts differed in the experts' score by only 0.02 on a 5-point scale.

Furthermore, it could be observed that various comments compare additive manufacturing with conventional manufacturing. The comments showed that although a part might be suitable for additive manufacturing, the conventional methods might be more economic, especially when considering post possessing with additive manufacturing.

Table 4.10: Feedback of the experts of the Delphi survey regarding the outcome of their own ranking

Make and model - Spare part	***Agree to place***	***Agree to all attributes***	***Comments***
Triumph TR6 – Trailing arm	83%	50%	rather forge … high AM cost … AM suitable production method … safety critical concerns…
BMW 328 – Brake shoes	83%	50%	Part made from 2 components … assembly necessary … rather iron cast … use AM for mould … friction pad not printable …
Jaguar E-type – Windscreen demister vents	67%	67%	Ideal for AM … higher up in ranking … Can you get a high margin on vents? …
Triumph TR4a – Exhaust manifold	50%	100%	Only one material is good … iron cast is also easy … very interesting for AM … might be uneconomic … rather place 4 …
Jaguar XK 150 – Dashboard Switches	67%	83%	Preferably machined … just a CNC program needed …
Mercedes 280 – Badges	67%	50%	High surface quality needed … post processing with AM needed … coating is expensive, not manufacturing … ideal for AM … better with conventional …
Average	69%	67%	

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Chapter 5

Case Study

5.1 Introduction

In addition to the research methodology of Knofius, van der Heijden and Zijm (2016), in this research the potential for a case study was identified. The purpose and aim of this case study were to collect information on the manufacturing process and its feasibilities.

To identify the best case for this case study a couple of constraints were set:

- The additive manufacturing material and process must be available at Stellenbosch University.
- The functionality and durability had to be tested in a suitable test stand.
- The part should have had an adequate complexity for the scope of a Master thesis.

To identify the case with the highest potential for additive manufacturing under the mentioned constraints, the database of the ranking was assessed. The part with the highest score was considered first. Table 5.1 shows the assessment of the database. The 8th part of the ranking was considered as feasible under the given constraints. The speedometer gear of a MG Midget MK1 from 1961 was chosen for this case study.

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Table 5.1: Selecting the spare part with the highest potential for additive manufacturing for the case study, which is appropriate for the scope of this research project

Score	*Make*	*Model*	*Part description*	*Material and process*	*Testing opportunity*	*Project complexity*
4,1	BMW	328	Brake shoes	No	No	Over scope
3,9	Jaguar	XK 150	Dashboard switch	Yes	Yes	Under scope
3,7	Triumph	Tr6	Hazard switch	Yes	Yes	Under scope
3,6	Mercedes	180D	Head Gasket	No	Yes	Over scope
3,5	Mercedes	280	Badges	Yes	Yes	Under scope
3,5	Borgward	Isabella Combi	Knobs	Yes	Yes	Under scope
3,5	Austin Healey	Sprite	Bonnet badge	Yes	Yes	Under scope
3,4	MG	Midget Mk1	Speedo gear	Yes	Yes	On scope

The assembly of the speedometer gear is shown in Figure 5.1. The part of the assembly which required a spare is the gear marked with the number 29. The gear assembly is mounted onto the gearbox and is driven by another gear which is located in the drive shaft of the gearbox. Both gears are made from plastic. The gear of Figure 5.1 is mounted on a metal shaft. The shaft is assembled in a sealed casing and is connected with a cable that turns the speedometer in the interior of the car.

Through internet research, a spare part (metal shaft and plastic gear) was found through the independent supply chain channel at a cost of 150 British-Pound (converted to R 3100). Since the function and design of speedometer gears are similar with other classic cars, a speedometer assembly of a Mazda 323 from 1989 was sourced from a local scrapyard. This second-hand assembly was used as an equivalent replacement for the gear of the MG and represented at the same time the test stand for a gear made with additive manufacturing.

(a) (b)

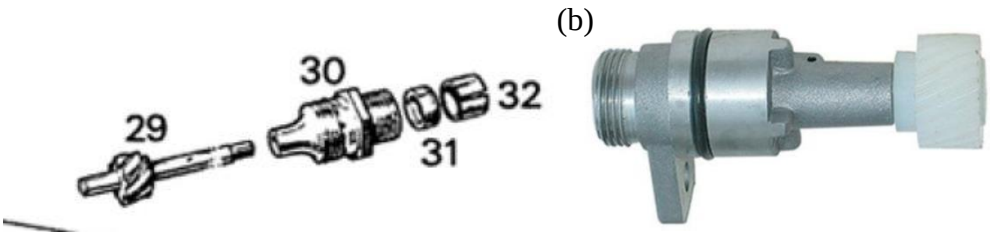

Figure 5.1(a) and (b): (a) The drawing of the original part from an MG Midget; (b) The test part from a Mazda 323 for the case study

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5.2 Manufacturing

The drawings of the original set of gears from the Mazda or the MG could not be found through internet research. Therefore, a set of gears with similar properties was designed to replace the original gears.

The set of gears was designed in Autodesk Inventor Professional 2022. The gears were manufactured in a Formlabs Form 3 machine which uses a plastic resin as raw material and the method SLA (stereolithography apparatus) to build the part. The SLA method was chosen over the FDM (fused deposition modelling) method because of its superior surface quality. Since the two gears will rotate with direct contact, the surface quality was identified as a key factor for a successful case study. The SLA and FDM method were the only two available additive manufacturing methods using plastic in the proposed research environment. All equipment used in this research are listed in Appendix A.

Two different types of material were available for this research project. One set of gears was made from Rigid 4000 (white colour), and three sets of gears were made from a blend of Rigid 4000 and Durable resign (orange colour). After the manufacturing process, all parts were cleaned and cured in compatible Form labs machines. The cost for manufacturing one set of gears was estimated at R 500. Examples of the resulting parts are shown in Figure 5.2. Last, the support structure was cut off and the surface, where the support structure was attached, was sanded.

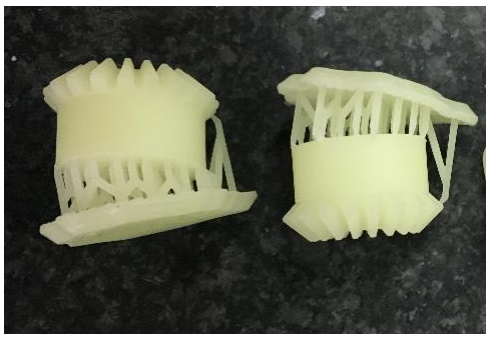

Figure 5.2: Green part of the additive manufactured gears, used this case study

5.3 Testing

The additive manufactured gears should resist the same operational condition as the original gears. For this research, it was not feasible to install the parts in the related car. The related car was not

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available, and the resources were not sufficient to test the gears in an endurance test. Therefore, a test stand was built which simulates the operational condition as best as possible. Figure 5.3 is a photo taken from the test stand while operating at full load.

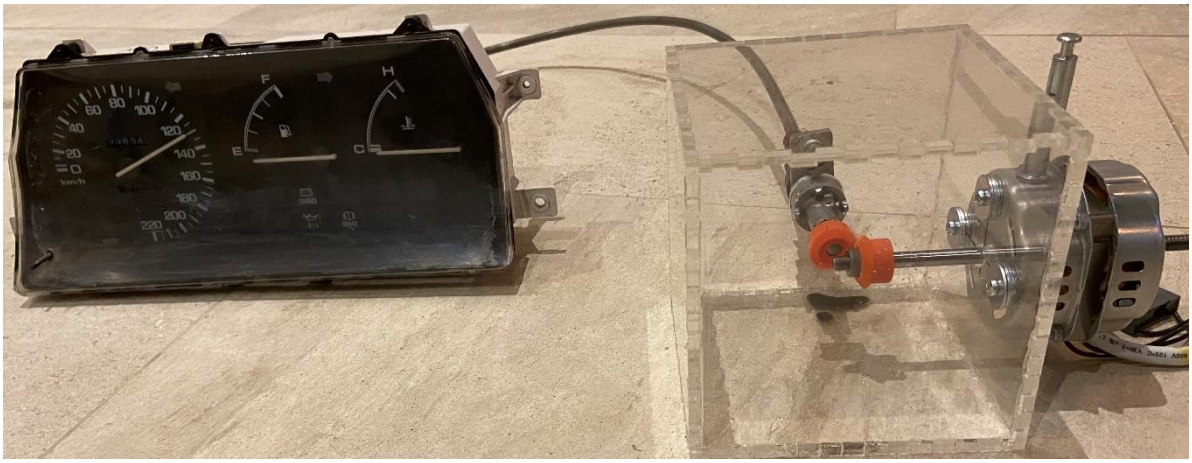

Figure 5.3: Test stand built for testing the additive manufactured gears

The operational condition of the gears in a gearbox is estimated in Table 5.2. Further, the measured test condition is stated. Major differences could be observed in the category's operational temperature and with the operational distance. Especially the reduced operational temperature could influence the results. The two additive manufacturing materials have a heat deflection temperature of about 40 degrees Celsius. Beyond that temperature, the material expands. However, the heat input could not be tested in this test stand. The two conditions however had in common, that the lubrication, rotation speed and the resistant forces were very similar.

Table 5.2: Comparison of the estimated operation condition and the test condition

Category	***Operation condition (estimates)***	***Test conditions***
Operational Temperature	-20 to 100 Degree Celsius	20 to 30 Degree Celsius
Lubrication	Gearbox oil	Gear grease
Rotation speed	-30 to 180 km/h	0 to 130 km/h
Operational distance	200,000 km	3,000 km
Resistant forces	Friction of cable and speedometer	Friction of cable and speedometer

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5.4 **Results**

After the gears were tested for 24 hours an equivalent of about 3,000km, the general wear and the surface condition were investigated. The general condition was measured by the analysis of the grease. Small plastic particles in the grease, only visible with the orange material, could have indicated wear. However, no plastic particles could be found in the grease. Due to limited laboratory access during the Corona pandemic, the surface wear was analysed with household products. A magnifier glass, with 30 and 60 zoom and the camera of a smartphone was used to record the test results.

Four sets of gears in two different designs were manufactured and tested. Since the results did not vary significantly with the design of the gear, only one design is visualised in Table 5.3. However, the results did vary with the material of the gears. Further, the results did also vary with the surface of the gear. Since the gears were only tested by spinning in one direction, one surface was exposed to higher forces than the other side of the teeth. Therefore, a photo of each surface of the two different materials were selected to present the results.

The gears made out of Rigid 4000 and Durable did not show any signs of wear. The plaided structure of the additive manufacturing process is still visible on the surface of the gears. The gears made from Rigid 4000 showed no wear on the surface with limited contact. However, the surface with contact to the other gear showed minor signs of wear. Three out of the 16 teeth showed these wear marks, just like the other gear of this set.

It must be considered that the test stand did not have the same tolerances then the assemblies of the automotive industry. A deviation in the assembly process of the gears could lead to inaccurate working conditions. Inaccurate working conditions means that the gears do not have maximum surface contact. A reduced surface contact would lead to an increased wear at the part of the surface which has contact. With regards to the result of the gear made from Rigid 4000, the wear on one part of the surface might be the result of inaccuracies of the test stand.

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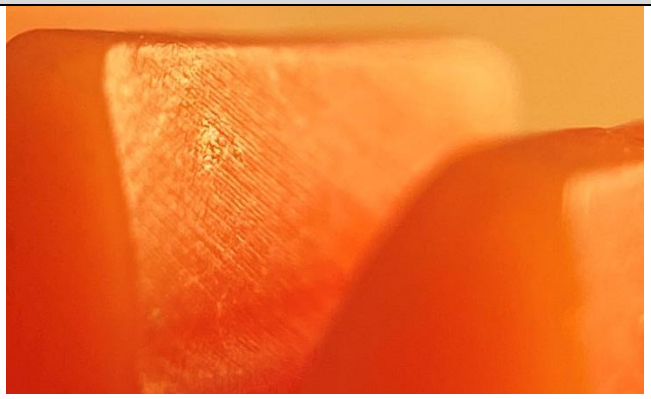
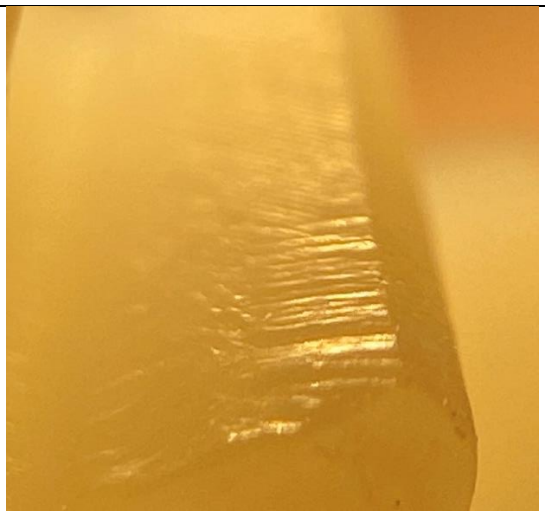
Table 5.3: Results of wear on the gear made from two materials after performing 3.000km on the test stand

	Rigid 4000 & durable blend	***Rigid 4000***
Surface with limited contact		
Surface with contact		

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Chapter 6
Discussion

6.1 Implementation approach

The case study proved that functional spare parts can be produced with additive manufacturing. With the information gained in the case study, a potential implementation strategy could be derived for this case. The implementation approach aimed to answer the question if the manufacturing process can be implemented at a centralized or decentralized level and how the additive manufacturing process can be integrated into the current spare part management of the automotive industry. This approach represented step 7 of the modified methodology by Knofius, van der Heijden and Zijm (2016)

Select a spare part

In the first step, an appropriate spare part assortment needed to be identified. In our case, spare parts of classic cars with unsatisfied demand were chosen as the spare part assortment. However, other spare part assortments may also show a high potential for additive manufacturing. For example, accessory parts might have a high potential for additive manufacturing. Accessory parts are sold to individualize and customize vehicles. With additive manufacturing, personalized parts could be sold in low volume. A second assortment with a proclaimed potential for additive manufacturing are parts with a risk for obsolescence. The risk for obsolescence can be reduced by producing these parts on-demand. Additive manufacturing is an ideal production method for on-demand services.

Nevertheless, whatever spare part assortment was chosen, relevant spare part attributes must be identified. Most often, the choice of attributes is limited to the availability of data in a database. In the case of classic car spare parts, no database was available. The customers indicated by providing customers goals that the non-availability of parts is the superior attribute. However, various other attributes influenced the final scores of the ranking. Therefore, it is recommended to choose a wide range of attributes and weigh them according to identified goals.

If the ranking is performed, it is recommended to access the highest rated parts further. The part with the highest score might not be feasible to produce with the available additive manufacturing

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machines. Therefore, it is sometimes beneficial to not choose the highest rated part, but rather the one which suits best to the available environment.

Design the spare part

The literature review and the case study highlighted that it is necessary to first design the spare part. In the case study, similar designs could be used. However, a spare part for commercial use has to be true to the original part. In the dependent supply chain channel, the car manufacturer or the original equipment manufacturer might have the data of the original parts. In contrast, these data are usually not available for the independent supply chain channel. If no data are available, the original part can be reverse engineered by utilizing, for example, 3d scanning techniques. In the case of the gear, the measurements of an original gear could be taken to replicate the design. The replication of the design however may also include design changes to improve the functionality, look or assembly process.

It must be considered that standards for commercially sold parts for the automotive industry exist. Therefore, despite the wear test conducted in this case study, further tests may be required before a part qualifies to be sold commercially.

Additive manufacturing the spare part

As soon as the tested spare part design is available, the part can be additive manufactured at every facility which has the necessary equipment. In the case of the gear, an SLA-additive manufacturing-machine, and clean and cure machines were required. Further, an authorized person who has the knowledge on how to use these machines is mandatory for the manufacturing process. The post processing of the gear required only basic knowledge and equipment.

Therefore, this case qualifies for a decentralized production close to where the customers' demand arises. It is conceivable that the spare part can be manufactured at the same workshop where the broken gear was identified.

However, some spare parts might not qualify for a decentralized production. Especially the three factors capacity utilisation, post-processing and knowledge availability have to be considered when choosing an implementation approach. For example, a medium size metal part like a piston does not qualify for a decentralized production yet. The capacity utilization of a metal additive manufacturing machine might not be given at a workshop. Post-processing with milling machines might be required and a qualified worker is mandatory to run these processes.

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Assembling the spare part

Furthermore, it needs to be considered that some spare parts need to be assembled before they are sold to the customer or to the workshop. In the case of the gear, it was mounted on a shaft. The connection between the gear and the shaft could be achieved by pressing the gear onto the shaft. This process has to be precise since the gear would be otherwise out of balance. Therefore, this process is not considered to be feasible at every workshop.

The assembly process could be simplified if the design of the gear and the shaft would be made compatible. In this case, the shaft and the gear would have to be additive manufactured. This would allow every mechanic to assemble the spare part according to the designed process. As a result, the production with additive manufacturing could be done at a decentralized level at the workshop. In addition, it could be investigated, if the manufacturing of the gear and the shaft as one part is feasible. This would illuminate the assembly process completely.

6.2 Impact of additive manufacturing on the spare part management of classic cars

To measure the potential impact of additive manufacturing, two models were presented. With the supply chain performance measurement model from the literature review, the current supply chain performance was analysed. With the same model, the improvements when using additive manufacturing could be measured. To measure the extent to which additive manufacturing is feasible to produce classic car spare parts, the modified ranking method was developed.

The results of the market survey showed that dissatisfaction with the spare part supply of classic cars exists. In addition, the supply chain performance measurement model with data from the literature review indicated that classic car spare parts are rarely supplied. The classic car owners agreed to the limited availability of spare parts. If spare parts were available, the price or the quality of the parts are the main reasons to cause dissatisfaction.

The modified ranking method indicated that 45 out of the 49 parts from the market survey are feasible for additive manufacturing. Furthermore, the case study highlighted that the additive manufacturing process required basic production and post processing equipment. The cost for the spare part could also be reduced.

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The impact of additive manufacturing on the spare part management can be concluded in the performance measurement model of Table 6.1.

Table 6.1: The impact of additive manufacturing on the supply chain performance of classic car spare parts

	Sub Level 1	***Sub Level 2***	***Input from the research methodology***
A. Quantitative	Cost	Distribution	• Distribution cost can be reduced to a minimum
		Manu-facturing & Warehouse	• The manufacturing of spare parts should be done on demand • Warehousing is not required
	Resource Utilisation	Labour, Machine, Energy	• For a good resource utilization, the right level of centralization must be chosen. • For the initial start-up, third party manufacturing centres could manufacture parts according to pre-determined specifications
B. Qualitative	Quality	Customer Dissatisfaction and Response time,	• High response time in contrast to conventional manufacturing • Individualization and variations opportunities for the customer and the part designer
		Stockout Probability	• On-demand production reduces the risk of obsolescence • On-demand production may increase the lead time
		Accuracy	• Additive manufacturing material and processes can meet automotive requirements • Newly designed parts have to be tested according to standards
	Flexibility	Output volume, Output variety	• Low output volumes are sufficient for classic car spare parts • One type of part can be customized towards different car designs
		Modifications, Integrating of new products	• High flexibility in the production • Independent as wells as dependent manufacturer can integrate additive manufactured products
	Visibility	Time, Accuracy	• The delivery time for components might be extended if the parts is produced on-demand

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			• Delivery times for non-available products are easier to estimate due to flexible production
	Trust	Consistency	• High trust in additive manufacturing • Customers are willing to accept different materials
	Innovative-ness	Launch of new products	• Component manufacturers can launch innovative products • Additional potential turnaround
		Use of new technology	• Component manufacturers can advertise the use of new technology

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Chapter 7
Conclusions and Outlook

7.1 Conclusion

The impact of additive manufacturing on the spare part management of classic cars was researched in this project. A literature review in combination with the supply chain performance measurement model indicated that the current performance, especially for spare parts of classic cars, is weak. The weak performance results from the relatively low demand for spare parts. The production and handling of low demand spare parts are for component manufacturers often not economic. Therefore, spare parts for classic cars are infrequently available. These findings got confirmed in the market survey, where classic car owners indicated that many spare parts are not available. If spare parts are available, the cost and quality of the parts cause frequent dissatisfaction. In addition, classic car owners are willing to purchase additive manufactured spare parts.

The modified ranking method ranked the spare parts from the market survey according to their potential for additive manufacturing. The results of this ranking showed that most parts are feasible for the production process and show potential when utilising additive manufacturing. It was observed that the parts with the highest potential showed a variety of attributes characteristics, for example, the spare part material. Including the opinion of subject-matter-experts, the following trend could be observed. Small parts like badges and interior knobs, most often made from plastic material, showed a high potential. Larger parts like the trailing arm or the brake shoe, most often made from metallic materials, showed a lower potential. Furthermore, the results showed that parts under heavy strain also have a lower potential than less functional parts.

The case study proved that it is feasible to produce the selected functional spare part with additive manufacturing. The test results of the working prototype showed limited wear after performing a trial under conditions close to reality. At the same time, the manufacturing cost for the prototype showed potential that a market ready part could be competitive with parts which are already available on the market. The discussion of the results from that case study and from the previously conducted research methods identified that additive manufacturing can be implemented, for many parts, at a decentralized

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level. Furthermore, the production of spare parts on demand was identified as a possible implementation approach.

Overall, from the manufacturing point of view, additive manufacturing can impact the current spare part management by producing many parts which are not available on the market. Vehicle specific components can be produced with additive manufacturing on time, in low volume and at reasonable costs. This flexibility in the production will have a positive impact on the supply chain performance. Simultaneously, classic car owners are willing to purchase additive manufactured parts and are willing to accept a change of material. Therefore, it can be concluded that additive manufacturing has a high potential to improve the spare part management of classic cars.

7.2 Contributions to practice

With this research project, three main contributions to practice are provided. Firstly, measurement variables of the classic car market, spare part management and additive manufacturing were identified and combined into a performance measurement model. Companies which are producing spare parts for classic cars can use these variables and apply the ranking method to their own spare part database. The outcome of this ranking can be used to start the production of selected spare parts. The outcome of this production will show, if the ranking requires adjustments, or if the part next on the list can be considered for production with additive manufacturing. In addition, the company can investigate the potential of producing on a centralised or decentralised level to improve the supply chain performance.

Secondly, the method is not exclusive to application for the classic car market but can also be applied throughout the automotive industry. This method can be applied to any industry which maintains ageing products with spare parts like the transportation, manufacturing, mining, or agriculture industry. By following the presented methodology, the prioritisation of parts can guide a company through the process of adopting additive manufacturing.

Lastly, additive manufacturing technology is continually evolving and therefore by adjusting the ranking methods variables, the latest features can be integrated into the ranking. This would ensure that companies stay aligned with the development of additive manufacturing and that the decisions based on the ranking method include the latest standards.

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7.3 Recommendations for future research

The following three recommendations for future research were concluded and are largely concerning future case studies. The first recommendation is based on the findings of this research. The results of the ranking method indicated that the vast majority of spare parts collected in the market survey (45 out of 49) are feasible for the production with additive manufacturing. This outcome was not expected since information from scoping literature highlighted limitations of additive manufacturing for automotive parts. Since this research was limited to one case study to prove the feasibility for AM the first recommendation for future research is to extend the feasibility tests to a multi case study. A spare part assortment which includes the full variety of spare part attributes like different materials, sizes, and functionalities could be selected and tested. The outcome of the multiple case study should highlight which spare parts can meet the identified potential from the ranking method. A subsequent analysis could identify which spare part attributes might limit the potential. Based on this experience, the ranking method could be improved by adjusting the weight of attributes, or by adding and removing attributes.

The second recommendation is based on the limitations of this research study. Due to the limited resources and the limitations given by the Covid-19 pandemic, the case study was performed under simulated conditions. For a future case study, it is recommended to perform the testing of parts according to the standards of both the automotive industry and the country where the parts should be sold. Through these enlarged tests, not only the feasibility, but also the market maturity of additive manufactured spare parts could be researched. The outcome of this study is presumed to reveal detailed information about the feasibility of additive manufacturing to produce classic car spare parts. However, based on this information, the impact of additive manufacturing on the whole automotive industry can be derived from, since the function of classic car parts does not vary much from part of modern cars.

The third recommendation is related to economic considerations. The single case study showed in a basic cost analysis that producing the part was more cost effective than buying the part on the market. However, this case study was focused on testing the feasibility for AM rather than performing a detailed profitability analysis. Therefore, it could be recommended to complement the above feasibility studies by a more detailed profitability analysis also including e.g. the invested resources

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for testing the spare parts. This extended financial analysis is presumed to contribute additional valuable information regarding the impact of additive manufacturing on the spare part management of classic cars.

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Appendix A Equipment for the case study

Case study equipment

Table A.1: Equipment used to perform the case study

Equipment	Description
Additive manufacturing machine	Formlabs Form 3: • Low Force Stereolithography (LFS)™ • XY Resolution: 25 microns • Laser Spot Size: 85 microns • Build Volume (WxDxH): 14.5 × 14.5 × 18.5 cm • Layer Thickness: 25 – 300 microns
Additive manufacturing material:	Material blends used: • Rigid 4000 • 60% Durable and 40% Rigid 4000
Cleaning machine	Form Wash: • Maximum Part Size (WxDxH): 14.5 × 14.5 × 17.5 cm • Solvent: IPA
Curing machine	Form Cure: • Dimensions (WxDxH): 26.2 x 26.2 x 34.0 cm • Maximum Cure Chamber: 80 °C
Test stand	Components: • Speedometer • Speedometer cable • Speedometer gear assembly • Singe phase 40W electric fan engine • Perspex box (WxDxH): 15 x 15 x 15 cm Auxiliary materials: • Gear grease • Smartphone camera • Magnifying glass • Sanding paper 600

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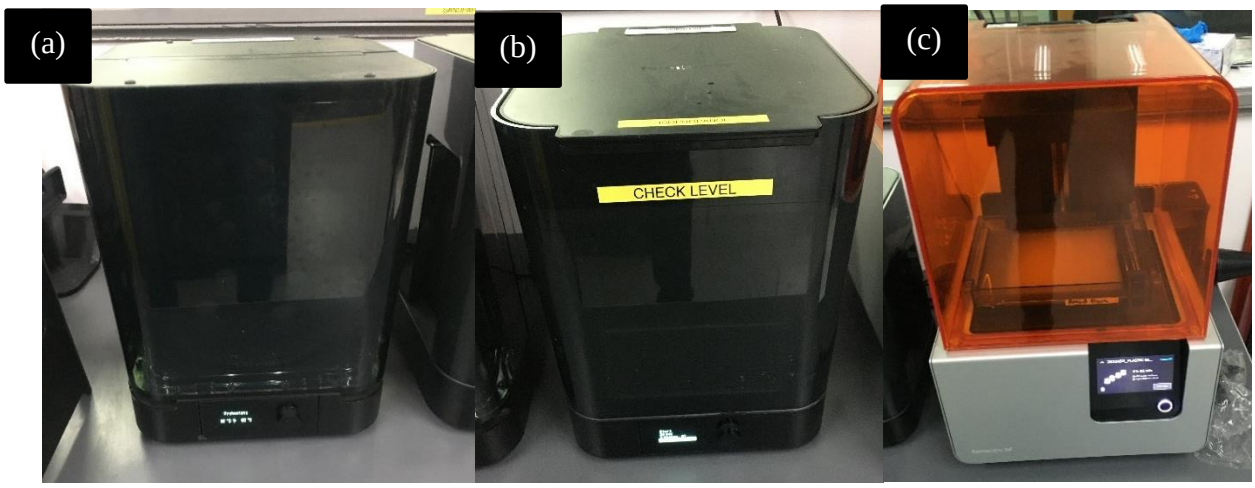

Figure A. 1 (a), (b) and (c): Formlabs machines at Stellenbosch University, Core- (a), clean- (b), SLA-machine (c)

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Appendix B: Survey questionnaires

Questionnaire of the market survey:

Confidential

Page 1

Spare Part Survey for Classic Cars

Welcome to the Spare Part Survey for Classic Cars. Please complete the survey below. Every participant contributes to an improved supply of spare parts for our beloved classic cars!

Thank you!

Please accept the Consent Information to enter the survey.

Please read the attached Consent Information carefully

[Attachment: "Consent_Information_Market_Survey.pdf"]

As the participant I hereby select the following option:	◯ I accept the invitation to participate in your research project, and if I decide to complete the questionnaire it would automatically mean that I have given consent for my responses to be used confidentially and anonymously. ◯ I decline the invitation to participate in your research project.

Please accept the Consent Information above to enter the survey.

09/04/2021 14:13 projectredcap.org REDCap

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Please enter the country you are located in.

- ◯ Afghanistan
- ◯ Albania
- ◯ Algeria
- ◯ Andorra
- ◯ Angola
- ◯ Argentina
- ◯ Armenia
- ◯ Australia
- ◯ Austria
- ◯ Azerbaijan
- ◯ The Bahamas
- ◯ Bahrain
- ◯ Bangladesh
- ◯ Belarus
- ◯ Belgium
- ◯ Bosnia and Herzegovina
- ◯ Botswana
- ◯ Brazil
- ◯ Bulgaria
- ◯ Cambodia
- ◯ Cameroon
- ◯ Canada
- ◯ Central African Republic
- ◯ Chad
- ◯ Chile
- ◯ China
- ◯ Colombia
- ◯ Congo
- ◯ Costa Rica
- ◯ Cote d'Ivoire
- ◯ Croatia
- ◯ Cuba
- ◯ Cyprus
- ◯ Czech Republic
- ◯ Denmark
- ◯ Dominican Republic
- ◯ Ecuador
- ◯ Egypt
- ◯ Ethiopia
- ◯ Finland
- ◯ France
- ◯ Gabon
- ◯ The Gambia
- ◯ Georgia
- ◯ Germany
- ◯ Ghana
- ◯ Greece
- ◯ Guinea
- ◯ Haiti
- ◯ Honduras
- ◯ Hungary
- ◯ Iceland
- ◯ India
- ◯ Indonesia
- ◯ Iran
- ◯ Iraq
- ◯ Ireland
- ◯ Israel
- ◯ Italy
- ◯ Jamaica
- ◯ Japan
- ◯ Jordan
- ◯ Kazakhstan
- ◯ Kenya
- ◯ Korea
- ◯ Kosovo
- ◯ Kuwait
- ◯ Laos
- ◯ Lebanon

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- ◯ Lesotho
- ◯ Liberia
- ◯ Libya
- ◯ Liechtenstein
- ◯ Lithuania
- ◯ Luxembourg
- ◯ Macedonia
- ◯ Madagascar
- ◯ Malawi
- ◯ Malaysia
- ◯ Maldives
- ◯ Mali
- ◯ Malta
- ◯ Mauritius
- ◯ Mexico
- ◯ Monaco
- ◯ Montenegro
- ◯ Morocco
- ◯ Mozambique
- ◯ Namibia
- ◯ Nepal
- ◯ Netherlands
- ◯ New Zealand
- ◯ Nicaragua
- ◯ Niger
- ◯ Nigeria
- ◯ Norway
- ◯ Oman
- ◯ Pakistan
- ◯ Paraguay
- ◯ Peru
- ◯ Philippines
- ◯ Poland
- ◯ Portugal
- ◯ Qatar
- ◯ Romania
- ◯ Russia
- ◯ Saudi Arabia
- ◯ Senegal
- ◯ Serbia
- ◯ Singapore
- ◯ Slovakia
- ◯ Slovenia
- ◯ South Africa
- ◯ Spain
- ◯ Sri Lanka
- ◯ Sudan
- ◯ Sweden
- ◯ Switzerland
- ◯ Tanzania
- ◯ Thailand
- ◯ Tunisia
- ◯ Turkey
- ◯ Uganda
- ◯ Ukraine
- ◯ United Arab Emirates
- ◯ United Kingdom
- ◯ United States of America
- ◯ Uruguay
- ◯ Venezuela
- ◯ Vietnam
- ◯ Yemen
- ◯ Zambia
- ◯ Zimbabwe
- ◯ Other

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Please enter your country if not listed above.	_____
Please enter your age group.	◯ 0-19 ◯ 20-29 ◯ 30-39 ◯ 40-49 ◯ 50-59 ◯ 60-69 ◯ 70-79 ◯ 80-89 ◯ 90-99

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Data of your Classic Car

How many classic cars have you already owned?

◯ 0 ◯ 1 ◯ 2 ◯ 3
◯ 4 ◯ 5 ◯ more than 5

You have indicated that you have already owned more than one classic car. For the following Survey, please focus on only one classic car with which you:

had the most problems finding spare parts are most familiar with

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Please enter the make of your classic car you will focus on in this survey.

- ◯ AC
- ◯ Alfa Romeo
- ◯ Aston Martin
- ◯ Audi
- ◯ Austin Healey
- ◯ Bentley
- ◯ BMW
- ◯ Borgward
- ◯ Brilliance
- ◯ Bugatti
- ◯ Buick
- ◯ BYD
- ◯ Cadillac
- ◯ Changan
- ◯ Chery
- ◯ Chevrolet
- ◯ Chrysler
- ◯ Citroen
- ◯ Daewoo
- ◯ Daihatsu
- ◯ Daimler
- ◯ Datsun
- ◯ Dodge
- ◯ Dongfeng
- ◯ FAW
- ◯ Ferrari
- ◯ Fiat
- ◯ Fisker
- ◯ Ford
- ◯ GAZ
- ◯ Geely
- ◯ Genesis
- ◯ GMC
- ◯ Great Wall
- ◯ Haval
- ◯ Holden
- ◯ Honda
- ◯ Hummer
- ◯ Hyundai
- ◯ Infiniti
- ◯ Isuzu
- ◯ Iveco
- ◯ Jaguar
- ◯ Jeep
- ◯ Kia
- ◯ Lada
- ◯ Lamborghini
- ◯ Lancia
- ◯ Land Rover
- ◯ Lexus
- ◯ Lifan
- ◯ Lincoln
- ◯ Lotus
- ◯ Marussia
- ◯ Maserati
- ◯ Maybach
- ◯ Mazda
- ◯ McLaren
- ◯ Mercedes
- ◯ Mercury
- ◯ MG
- ◯ Mini
- ◯ Mitsubishi
- ◯ Morgan
- ◯ Morris
- ◯ Nissan
- ◯ Noble
- ◯ Opel
- ◯ Peugeot

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- ◯ Plymouth
- ◯ Pontiac
- ◯ Porsche
- ◯ Renault
- ◯ Rolls-Royce
- ◯ Rover
- ◯ Saab
- ◯ Saturn
- ◯ Scion
- ◯ Seat
- ◯ Skoda
- ◯ Smart
- ◯ Ssang Yong
- ◯ Subaru
- ◯ Suzuki
- ◯ Tata
- ◯ Tesla
- ◯ Toyota
- ◯ Trabant
- ◯ Triumph
- ◯ TVR
- ◯ Vauxhall
- ◯ Volkswagen
- ◯ Volvo
- ◯ Wartburg
- ◯ Other Make

If your make was not listed, please type in your make.

_____

Please enter the model name.

_____

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Please enter the Year of Production of your [make] [car_model]	◯ 2021 ◯ 2020 ◯ 2019 ◯ 2018 ◯ 2017 ◯ 2016 ◯ 2015 ◯ 2014 ◯ 2013 ◯ 2012 ◯ 2011 ◯ 2010 ◯ 2009 ◯ 2008 ◯ 2007 ◯ 2006 ◯ 2005 ◯ 2004 ◯ 2003 ◯ 2002 ◯ 2001 ◯ 2000 ◯ 1999 ◯ 1998 ◯ 1997 ◯ 1996 ◯ 1995 ◯ 1994 ◯ 1993 ◯ 1992 ◯ 1991 ◯ 1990 ◯ 1989 ◯ 1988 ◯ 1987 ◯ 1986 ◯ 1985 ◯ 1984 ◯ 1983 ◯ 1982 ◯ 1981 ◯ 1980 ◯ 1979 ◯ 1978 ◯ 1977 ◯ 1976 ◯ 1975 ◯ 1974 ◯ 1973 ◯ 1972 ◯ 1971 ◯ 1970 ◯ 1969 ◯ 1968 ◯ 1967 ◯ 1966 ◯ 1965 ◯ 1964 ◯ 1963 ◯ 1962 ◯ 1961 ◯ 1960 ◯ 1959 ◯ 1958 ◯ 1957 ◯ 1956 ◯ 1955 ◯ 1954 ◯ 1953

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	◯ 1952 ◯ 1951 ◯ 1950 ◯ Older then 1950
If the Year of Production is before then 1950, please type in the Year of Production	_____
Please indicate the current value of your [make] [car_model]	◯ below 10,000€ ◯ 10, 000€ to 25.000€ ◯ 25,000 to 75,000€ ◯ 75,000€ to 150,000€ ◯ above 150.000€

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Spare part data

Please determine the overall level of difficulty for sourcing a spare part for your [make] [car_model]	◯ Very difficult (many spare parts are not available) ◯ Difficult (some spare parts are not available or very expensive) ◯ Neutral ◯ Good (most spare parts are available at a moderate price) ◯ Very good (all spare parts are directly available at low prices)

You have indicated that spare parts of your [make] [car_model] were not available. For the following survey, please focus on only one spare part which is:

most difficult to find or crucial for the driving experience or reducing your classic cars value the most

Please select the assembly group to which the spare part belongs	◯ Engine ◯ Drive train ◯ Cooling system ◯ Fuel mixture system and air intake ◯ Suspension and steering ◯ Manifold and exhaust system ◯ Brakes ◯ Electrics, ignition system, heating and dashboard instruments ◯ Body panels and body fittings ◯ Seats and interior trim ◯ Other
Please select from the following Engine parts or assemblies	◯ Gaskets ◯ Engine Timing Control ◯ Accessory Belt, Drive Systems ◯ Engine Mountings ◯ Engine block ◯ Cylinder Head ◯ Camshaft ◯ Crankshaft ◯ Intermediate/ Balancer Shaft ◯ Valves, Parts ◯ Connecting Rod ◯ Piston Assembly ◯ Crankcase ◯ Crankcase breathing ◯ Other
Please select from the following Drive Train parts or assemblies	◯ Gaskets ◯ Bearings ◯ Covers ◯ Countershaft, Transmission ◯ Synchronizing system, Transmission ◯ Main Shaft, Transmission ◯ Gearwheel, Transmission ◯ Differential ◯ Clutch plate ◯ Clutch cover ◯ Clutch bearing ◯ Driveshaft ◯ Other
Please select from the following Cooling system parts or assemblies	◯ Water Pump ◯ Thermostat ◯ Radiator ◯ Expansion Tank, Engine Coolant ◯ Hoses ◯ Pipes ◯ Radiator Fan ◯ Oil Cooler ◯ Intercooler, Charger ◯ Other

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Please select from the following Fuel Mixture System and Air Intake parts or assemblies	◯ Fuel pump ◯ Fuel lines ◯ Fuel filter ◯ Intake manifold ◯ Air intake hose ◯ Airfilter housing ◯ Throttle Blade ◯ Mass Airflow sensor, Airflow meter ◯ Injection Pump ◯ Injectors ◯ Carburettor ◯ Other
Please select from the following Suspension and Steering parts or assemblies	◯ Steering Rack ◯ Hydraulic Pump, Power Steering ◯ Pressure Hose or Pipe ◯ Tie Rod Assembly ◯ Suspension spring ◯ Spring cap ◯ Spring mounting ◯ Bump stop, Suspension ◯ Suspension Strut ◯ Shock Absorber ◯ Steering Links ◯ Stabilizer ◯ Struts, Rods ◯ Torque rod ◯ Axle Support, Body Sub-Frame ◯ Bushing ◯ Suspension cross brace ◯ Wheel bearing ◯ Wheel hub ◯ Other
Please select from the following Manifold and Exhaust system parts or assembly	◯ Exhaust system ◯ Manifold ◯ Downpipe ◯ Silencer ◯ Pipes ◯ Heatshield ◯ Turbocharger ◯ Other
Please select from the following Breaks parts or assembly	◯ Disc Brake ◯ Drum Brake ◯ Handbrake ◯ Brake Hoses, -Pipes ◯ Brake Master Cylinder ◯ Brake Calipers ◯ Brake Regulator System ◯ Brake Booster ◯ Other
Please select from the following Electrics parts or assembly	◯ Lights ◯ Indicator ◯ Alternator ◯ Starter ◯ Ignition ◯ Battery ◯ Relais ◯ Switches ◯ Sender Units, Sensors ◯ Fuses ◯ Horn ◯ Instruments ◯ Cruise Control ◯ Audio / Communication ◯ Wiring Harness incl. Connector housing ◯ Control units ◯ Other

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Please select from the following Body Panels and Body Fittings parts or assembly	◯ Trim parts ◯ Bumpers ◯ Bootlid ◯ Bonnet ◯ Doors ◯ Emblems ◯ Sunroof ◯ Fenders ◯ Radiator grill ◯ Engine compartment ◯ Reflectors ◯ Spoiler ◯ Windscreen ◯ Rear window ◯ Side Window ◯ Window seal ◯ Window frame ◯ Door mirrors ◯ Other
Please select from the following Seats and Interieur trim parts or assembly	◯ Dashboard ◯ Center console ◯ Ashtray ◯ Handles ◯ Headliner ◯ Steering Wheel ◯ Ventilation ◯ Pedals ◯ Safety Belt System ◯ Seat mounting ◯ Seat adjustment ◯ Armrest ◯ Upholstery ◯ Sun visor ◯ Carpet ◯ Panels ◯ Sill plate ◯ Cigarette Lighter ◯ Other
Please name your selected spare part as accurately as possible	_____
Is your selected spare part available at the car manufacturer (e.g. Audi) or at the original equipment supplier (e.g. Bosch)?	◯ Yes ◯ No
Which specific problems have you experienced with the selected spare part? (multiple replies possible)	☐ Not always available ☐ Exorbitant price ☐ Exorbitant delivery cost ☐ Exorbitant delivery time ☐ Poor quality ☐ Spare part was not true to the original ☐ Other difficulties
Which other problems have you been facing?	_____
Is your selected spare part available at the Aftermarket?	◯ Yes ◯ No
Which specific problems have you experienced with the spare part from the Aftermarket? (multiple replies possible)	☐ Spare part was not available ☐ Exorbitant price ☐ Exorbitant delivery cost ☐ Exorbitant delivery time ☐ Poor quality ☐ Spare part was not true to the original ☐ Other difficulties
Which other problems have you been facing?	_____
You have answered that the spare part was not available. Did the supplier give you a delivery period when the spare part will be available again?	◯ Yes ◯ No
Please insert the delivery period in the unit "days"	_____

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Please indicate the urgency to receive the spare part for the purpose of driving/selling/presenting your classic car	◯ Very urgent ◯ Urgent ◯ Neutral ◯ Not urgent ◯ Can do without the spare
Please estimate the size of your spare part by comparing it with a standard 10 Liter water bucket (about 25x25x25cm).	◯ Much smaller than a 10 Liter water bucket ◯ Slightly smaller than a 10 Liter water bucket ◯ About the same volume as a 10 Liter water bucket ◯ Slightly larger than a 10 Liter water bucket ◯ Very much larger than a 10 Liter water bucket
Please enter the material that the part is originally made of. (multiple replies possible)	☐ Plastic ☐ Bakelite ☐ Rubber ☐ Steel ☐ Aluminium ☐ Glass ☐ Fiberglass ☐ No Information ☐ Other
Please enter the material that the part is originally made of	_____
What delivery period does the dealer offer you for the spare part?	◯ Less than 3 days ◯ Less than 1 week ◯ Less than 1 month ◯ More than 1 month ◯ No information
What delivery period do you prefer for the spare part?	◯ Less than 3 days ◯ Less than 1 week ◯ Less than 1 month ◯ More than 1 month ◯ Not relevant
Does your spare part have the potential for improvements in Design or Functionality?	◯ Very high potential ◯ High potential ◯ Maybe ◯ Low potential ◯ No potential
Please name and describe these improvements	_____
Does an individualisation on your spare part justify an increase in price?	◯ Price does not matter ◯ Significant increase ◯ Increase ◯ Slight increase ◯ No increase

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You as the owner of a [make] [car_model] prefers buying spare parts _____. (multiple replies possible)	☐ directly from the car manufacturer ☐ from the original equipment manufacturer (e.g. Bosch) ☐ from an independent spare part manufacturer ☐ second hand ☐ from any source which is trustworthy ☐ from the source which is most affordable ☐ form other sources which are not mentioned
Please name the source which was not mentioned	_____
You have answered that you like buying new and genuine spare parts. Please select the reasons for your choice. (multiple replies possible)	☐ Genuine parts have consistently high quality ☐ Genuine parts are beneficial for the value of my vehicle ☐ Genuine parts offer the best value for money ☐ Car manufacturers have good ordering systems ☐ Car manufacturers have the biggest variety of spare parts ☐ Car manufacturers have the highest delivery capability ☐ Car manufacturers have the shortest delivery times ☐ Other reasons
Please provide other reasons why you prefer buying genuine parts.	_____
You have indicated that you like buying parts from independent sources. Please select the reasons for that choice. (multiple replies possible)	☐ Non-genuine parts have consistently high quality ☐ Non-genuine parts are beneficial for the value of my vehicle ☐ Non-genuine parts offer the best value for money ☐ Independent suppliers have good ordering systems ☐ Independent suppliers have the biggest variety of spare parts ☐ Independent suppliers have the highest delivery capability ☐ Independent suppliers have the shortest delivery times ☐ Other reasons
Please provide other reasons why you buy from independent sources.	_____

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Please indicate what goals you are pursuing when purchasing spare parts:

Please indicate your preference:

Low Part Prices vs. Short Delivery Time

Low Part Price | Neutral | Short Delivery Time

(Place a mark on the scale above)

Please indicate your preference:

Original Part vs. Improved Replica Part

Originallity | Neutral | Improved Replica

(Place a mark on the scale above)

Please indicate your preference:

Low Part Price vs. High Reliability

Low Part Price | Neutral | High Reliablity

(Place a mark on the scale above)

Please indicate your preference:

Low Delivery Cost vs. Short Delivery Time?

Low Delivery Cost | Neutral | Short Delivery Time

(Place a mark on the scale above)

Please indicate your preference:

Original Part vs. Individualised Part

Originallity | Neutral | Individualised Part

(Place a mark on the scale above)

Please indicate your preference:

Traditional Supplier vs. New Innovative Supplier

Traditional Supplier | Neutral | New Innovative Supplier

(Place a mark on the scale above)

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Additive Manufacturing for spare parts of classic cars	
Please indicate your level of knowledge about Additive manufacturing	◯ Very limited knowledge ◯ Basic knowledge ◯ Average knowledge ◯ Advanced knowledge ◯ Expert knowledge
My trust in Additive manufactured for spare parts is_____	◯ Very high ◯ High ◯ Neutral ◯ Low ◯ Very low
Additive manufacturing is an interesting production method and I would like to purchase these parts for my vehicle	◯ Strongly agree ◯ Agree ◯ Neutral ◯ Disagree ◯ Strongly disagree
Which supplier do you prefer for spare parts produced with additive manufacturing? (multiple replies possible)	☐ The car manufacturer (e.g. Audi, BMW, Porsche...) ☐ The original equipment manufacturer (e.g. Bosch...) ☐ An independent supplier ☐ Any supplier which seems trustworthy
Do you accept a different material than the original, if the new material offers the same performance	◯ Yes ◯ No ◯ Maybe

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Lucky Draw

Please enter your E-MAIL address to enter the Lucky Draw _____

Stand the chance of winning a personalized emblem with your name and your car printed on it. This emblem will be produced with Additive Manufacturing. More information will be sent via E-mail.

If you would like to benefit in future from an increased spare part offer, please start the survey again and enter other spare parts. To do so, please click the SUBMIT button.

Please SHARE the link to the survey with your friends and other classic car enthusiasts. I highly appreciate your support.

Thank you for participating!

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Questionnaire of the first round of the Delphi survey:

Confidential

Delphi Survey Round 1

Welcome to the Delphi Survey with experts from the field of Additive Manufacturing and Spare Part Management.
Please read and sign the consent form to enter the survey

[Attachment: "Consent- Info-Delphi-survey.pdf"]

Please select ACCEPT, if you agree to the consent form

- ○ I accept the invitation to participate in your research project, and if I decide to complete the questionnaire it would automatically mean that I have given consent for my responses to be used confidentially and anonymously.
- ○ I decline the invitation to participate in your research project.

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Questions about your person...

If you haven't watched the INTRODUCTION VIDEO yet, please click on the YouTube link.

Please select your USER PROFIL	◯ Car Manufacturer - Classic_Department_Employee ◯ Car Manufacturer - After_Sales_Employee ◯ Car Manufacturer - After_Sales_Team_Leader ◯ Car Manufacturer - Additive_Manufacturing ◯ Aftermarket - Business_Owner ◯ Consultant - Head_of_Technology ◯ Machine_Supplier - Consultant ◯ Researcher_South_Afirca ◯ Researcher_Netherlands ◯ Lecturer - Production Methods ◯ Random_Sample - Classic_Car_Owner ◯ Other User
Please enter your alternative Username and your email for correspondence	_____
Please indicate your level of knowledge on CLASSIC CARS	◯ Very good ◯ Good ◯ Average ◯ Low ◯ Very low
Please indicate your level of knowledge on the SPARE PART MANAGEMENT in the automotive industry	◯ Very good ◯ Good ◯ Average ◯ Low ◯ Very low
Please indicate your level of knowledge on ADDITIVE MANUFACTURING	◯ Very good ◯ Good ◯ Average ◯ Low ◯ Very low

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Warm-Up Questions **Please react to the Statements:**	
Additive Manufacturing has the highest potential for producing NON-AVAILABLE spare parts.	◯ Strongly agree ◯ Agree ◯ Neutral ◯ Disagree ◯ Strongly disagree
Additive Manufacturing has the highest potential for producing LOW DEMAND spare parts.	◯ Strongly agree ◯ Agree ◯ Neutral ◯ Disagree ◯ Strongly disagree
Additive Manufacturing is competitive to conventional manufacturing for producing HIGH VOLUME spare parts.	◯ Strongly agree ◯ Agree ◯ Neutral ◯ Disagree ◯ Strongly disagree
In future, Additive Manufacturing will disrupt the current SUPPLY CHAIN for spare parts.	◯ Strongly agree ◯ Agree ◯ Neutral ◯ Disagree ◯ Strongly disagree

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Please identify spare parts attributes that have an influence on the potential of Additive Manufacturing for producing classic car spare parts.

The following sub-categories will give GUIDANCE for your responses:

1. Spare Part Management related attributes

1.1 Spare part market related

1.2 Manufacturer related

1.3 Supply Chain related

2. Production related attributes

2.1 Design related

2.2 Function related

2.3 Characteristic related

1.1 SPARE PART MARKET related attributes, for example:	☐ Demand Rate ☐ Part Availability
.... other SPARE PART MARKET related attributes	_____ (Only one attribute)
.... other SPARE PART MARKET related attributes	_____ (Only one attribute)
1.2 CAR BRAND and MODEL related attributes, for example	☐ Vehicles Value ☐ Spare Part Price ☐ Available Spare Part Quality
.... other CAR BRAND and MODEL related attributes	_____
.... other CAR BRAND and MODEL related attributes	_____
1.3 SUPPLY CHAIN related attributes, for example:	☐ Remanufacturing lead time ☐ Remanufacturing cost ☐ Warehousing cost ☐ Obsolescence risk
.... other SUPPLY CHAIN related attributes	_____

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.... other SUPPLY CHAIN related attributes

_____

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2. Production related attributes	
2.1 SPARE PART DESIGN related attributes, for example:	☐ Part Size ☐ Geometry
.... other DESIGN related attributes	_____ (Only one attribute)
.... other DESIGN related attributes	_____ (Only one attribute)
2.2 SPARE PART FUNCTION related attributes, for example:	☐ Mechanical requirements ☐ Thermal requirements
.... other FUNCTION related attributes	_____ (Only one attribute)
.... other FUNCTION related attributes	_____ (Only one attribute)
2.3 SPARE PART CHARACTERISTIC related attributes, for example:	☐ Material
.... other CHARACTERISTIC related attributes	_____ (Only one attribute)
.... other CHARACTERISTIC related attributes	_____ (Only one attribute)

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Weigh your selected spare part attributes according to its importance.			
Level of importance of attribute "Demand Rate"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Part Availability"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[market_attribute_1]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[market_attribute_2]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Vehicles Value"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Spare Part Price"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Available Spare Part Quality"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[make_attribute_1]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[make_attribute_2]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Remanufacturing Lead Time"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Remanufacturing Cost"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Warehousing Cost"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Obsolescence Risk"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	

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Level of importance of attribute "[supplychain_attribute_1]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[supplychain_attribute_2]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Part Size"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Geometry"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[design_attribute_1]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[design_attribute_2]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Mechanical Requirements"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Thermal Requirements"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[function_attribute_1]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[function_attribute_2]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "Material Type"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	
Level of importance of attribute "[characteristic_attribute_1]"	Less Important	Neutral	Very Important
		(Place a mark on the scale above)	

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Level of importance of attribute "[characteristic_attribute_2]"

Less Important | Neutral | Very Important

(Place a mark on the scale above)

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Questionnaire of the second round of the Delphi survey:

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Page 1

Delphi Survey Round 2/3

Welcome to the 2. Part of the Delphi Survey

Please select your USER PROFILE

- ◯ Car Manufacturer - Classic_Department_Employee
- ◯ Car Manufacturer - After_Sales_Employee
- ◯ Car Manufacturer - After_Sales_Team_Leader
- ◯ Aftermarket - Business_Owner
- ◯ Consultant - Head_of_Technology
- ◯ Researcher_South_Afirca
- ◯ Researcher_Netherlands
- ◯ Lecturer - Production Methods

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TRIUMPH TR6, Trailing Arm

Model: Triumph TR6, 1976
Part: Trailing Arm,
Material: Aluminium Cast
Not available, Urgent replacement

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The DEMAND RATE for this part is ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The CURRENT PART COST are expected to be ____ (Part Price, Vehicles Value)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The REMANUFACTURING COST & TIME for this part are ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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The STORAGE SUITABILITY for this part is _____ (Warehousing Cost, Obsolescence Risk)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The LEVEL OF STRESS for this part is _____ (Mechanical, Thermal, Chemical Requirements, Certification)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The SUITABILITY FOR ADDITIVE MANUFACTURING for this part is _____ (Material Availability., Surface, Colour, Size, Geometry)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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BMW 328, Brake Shoe

Model: BMW 328, 1937
Part: Brake Shoe
Materials: Steel plate and friction material
Not available, Urgent replacement

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[redacted]

Blacked out for privacy reasons

The DEMAND RATE for this part is ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The CURRENT PART COST are expected to be ____ (Part Price, Vehicles Value)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The REMANUFACTURING COST & TIME for this part are ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The STORAGE SUITABILITY for this part is ____ (Warehousing Cost, Obsolescence Risk)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
Please select which subcomponent should be printed (Multiple answers possible)	☐ Iron Cast Brake shoe ☐ Brake Pad

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The LEVEL OF STRESS for the part(s) is _____ (Mechanical, Thermal, Chemical Requirements, Certification)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The SUITABILITY FOR ADDITIVE MANUFACTURING for the part(s) is _____ (Material Availability., Surface, Colour, Size, Geometry)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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Triumph TR4a, Exhaust manifold

Model: Triumph TR4a,
Part: Exhaust manifold
Materials: Cast iron
Not available, Not urgent

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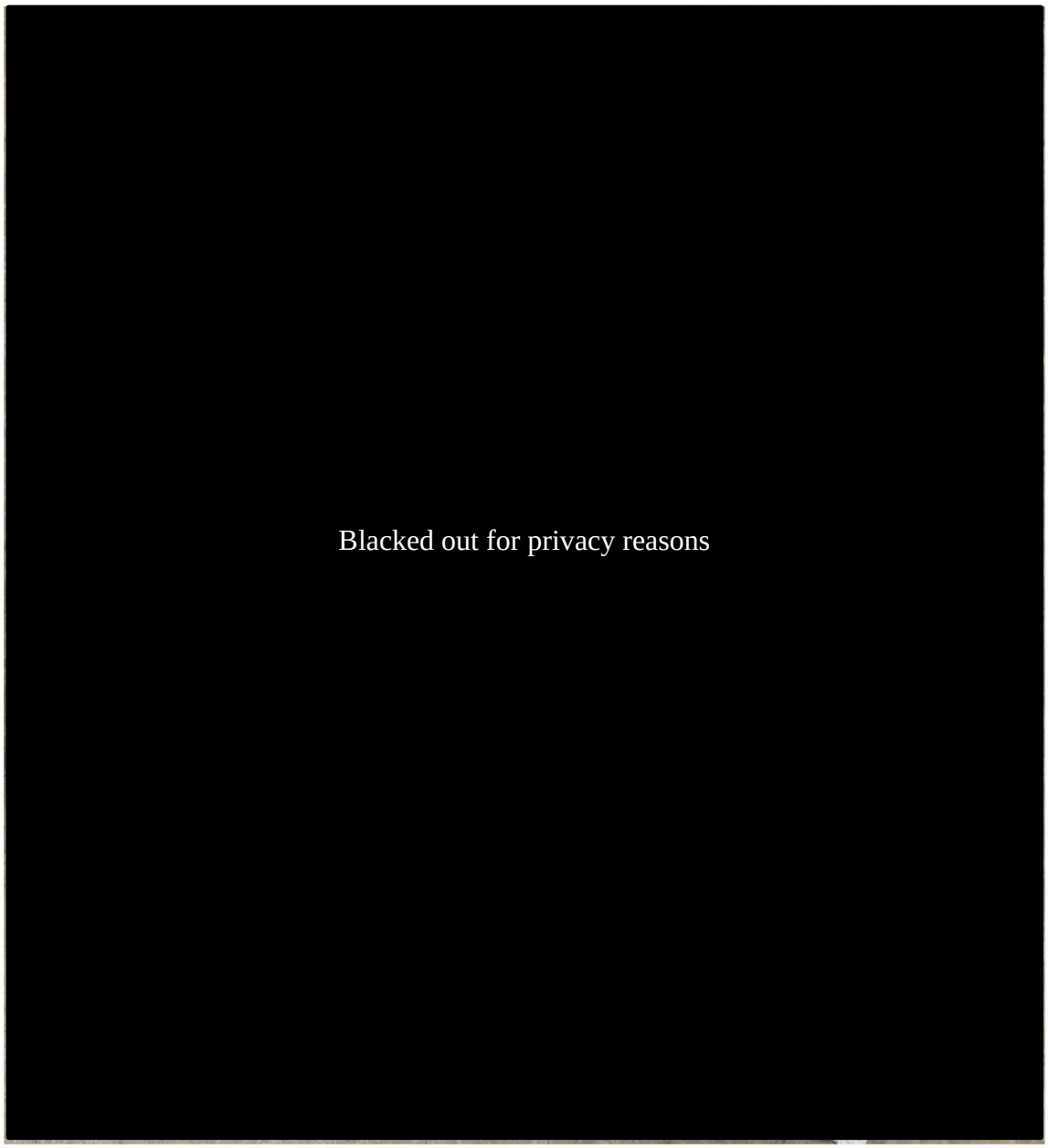

The DEMAND RATE for this part is ____

- ◯ Very High
- ◯ High
- ◯ Neutral
- ◯ Low
- ◯ Very Low

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The CURRENT PART COST are expected to be ____ (Part Price, Vehicles Value)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The REMANUFACTURING COST & TIME for this part are ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The STORAGE SUITABILITY for this part is ____ (Warehousing Cost, Obsolescence Risk)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The LEVEL OF STRESS for this part is ____ (Mechanical, Thermal, Chemical Requirements, Certification)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The SUITABILITY FOR ADDITIVE MANUFACTURING for this part is ____ (Material Availability., Surface, Colour, Size, Geometry)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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Mercedes 280, Badge

Model: Mercedes 280, 1983
Part: Trunk badge
Materials: Plastic
Not available, neutral urgency

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The DEMAND RATE for this part is ____

- ◯ Very High
- ◯ High
- ◯ Neutral
- ◯ Low
- ◯ Very Low

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The CURRENT PART COST are expected to be ____ (Part Price, Vehicles Value)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The REMANUFACTURING COST & TIME for this part are ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The STORAGE SUITABILITY for this part is ____ (Warehousing Cost, Obsolescence Risk)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The LEVEL OF STRESS for this part is ____ (Mechanical, Thermal, Chemical Requirements, Certification)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The SUITABILITY FOR ADDITIVE MANUFACTURING for this part is ____ (Material Availability., Surface, Colour, Size, Geometry)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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Jaguar E-type, Windshield demister vents

Model: Jaguar E-Type, 1967
Part: Windschield demister vents
Materials: Iron cast
Aftermarkt availability but poor quality, neutral urgency

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[redacted]

Blacked out for privacy reasons

The DEMAND RATE for this part is ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The CURRENT PART COST are expected to be ____ (Part Price, Vehicles Value)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The REMANUFACTURING COST & TIME for this part are ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The STORAGE SUITABILITY for this part is ____ (Warehousing Cost, Obsolescence Risk)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The LEVEL OF STRESS for this part is ____ (Mechanical, Thermal, Chemical Requirements, Certification)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The SUITABILITY FOR ADDITIVE MANUFACTURING for this part is ____ (Material Availability., Surface, Colour, Size, Geometry)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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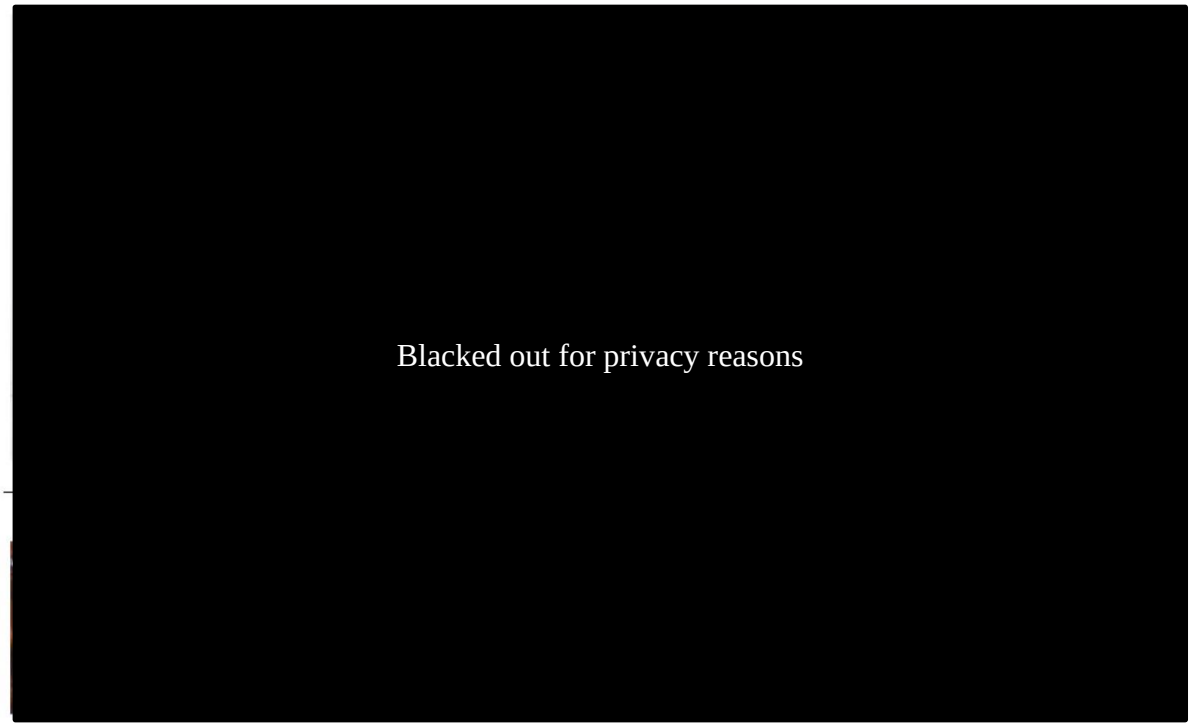
Jaguar XK 150, Dash board switches

Model: Jaguar XK 150, 1959
Part: Dash board switches
Materials: Bakelite and aluminium
Not available, neutral urgency



The DEMAND RATE for this part is ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The CURRENT PART COST are expected to be ____ (Part Price, Vehicles Value)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The REMANUFACTURING COST & TIME for this part are ____	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The STORAGE SUITABILITY for this part is ____ (Warehousing Cost, Obsolescence Risk)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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Please select which subcomponent should be printed (Multiple answers possible)	☐ Bakelite knob ☐ Aluminium surrounding
The LEVEL OF STRESS for this part is _____ (Mechanical, Thermal, Chemical Requirements, Certification)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low
The SUITABILITY FOR ADDITIVE MANUFACTURING for this part is _____ (Material Availability., Surface, Colour, Size, Geometry)	◯ Very High ◯ High ◯ Neutral ◯ Low ◯ Very Low

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Questionnaire of the third round of the Delphi survey:

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Page 1

Delphi Survey Round 3/3

Please complete the survey below.

Thank you!

Please select your USER PROFILE:

- ◯ Car Manufacturer - Classic_Department_Employee
- ◯ Car Manufacturer - After_Sales_Employee
- ◯ Car Manufacturer - After_Sales_Team_Leader
- ◯ Aftermarket - Business_Owner
- ◯ Consultant - Head_of_Technology
- ◯ Researcher_Netherlands
- ◯ Lecturer - Production Methods

Please watch the INTRODUCTION VIDEO before starting the survey

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Results: Places 6 to 4

Explanation of the SCORING of ATTRIBUTES:

High Score for ADDITIVE MANUFACTURING if Suitability for AM is good. High Score for LEVEL OF STRESS if Level of Stress is Low, which is good for AM. High Score for REMANUFACTURING if Remanufacture with Conventional Production Methods is Difficult, which is a Potential for AM. High Score for PART AVAILABILITY if the part is not available, which is a potential for AM. High Score for STORAGE SUITABILITY if Storage Suitability is Low, which is a potential for On-Demand production with AM. High Score for DEMAND RATE if Demand Rate is Low, which is an advantage of AM High Score for CURRENT PART COSTS if Current Part Costs are High, which is a potential for AM to reduce costs.

6th Place: Trailing Arm

(The higher a score of an attribute, the higher the potential for utilizing Additive Manufacturing)

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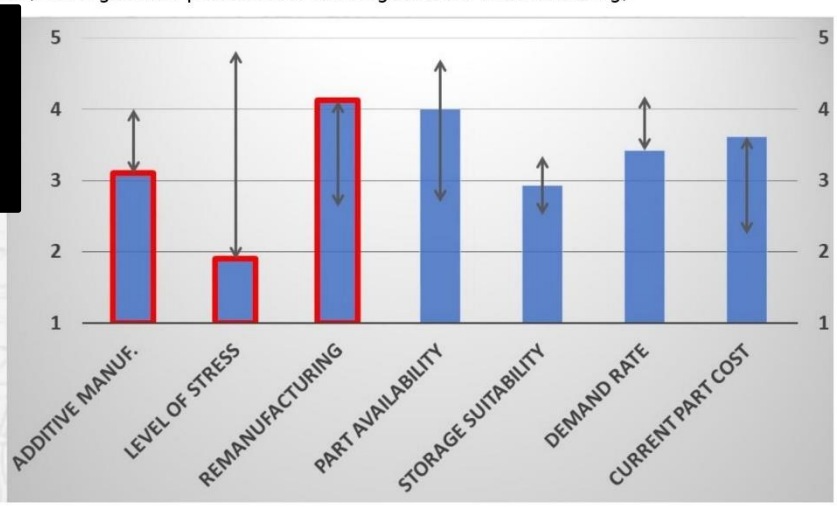
Place 6
Score: 3.27



Do you AGREE with the 6th Place? ◯ Yes ◯ No

Do you AGREE with all ATTRIBUTES SCORES? ◯ Yes ◯ No

Please provide additional FEEDBACK regarding the outcome of the ranking:

Different place of this part? Different scores of attributes? Additional feedback?

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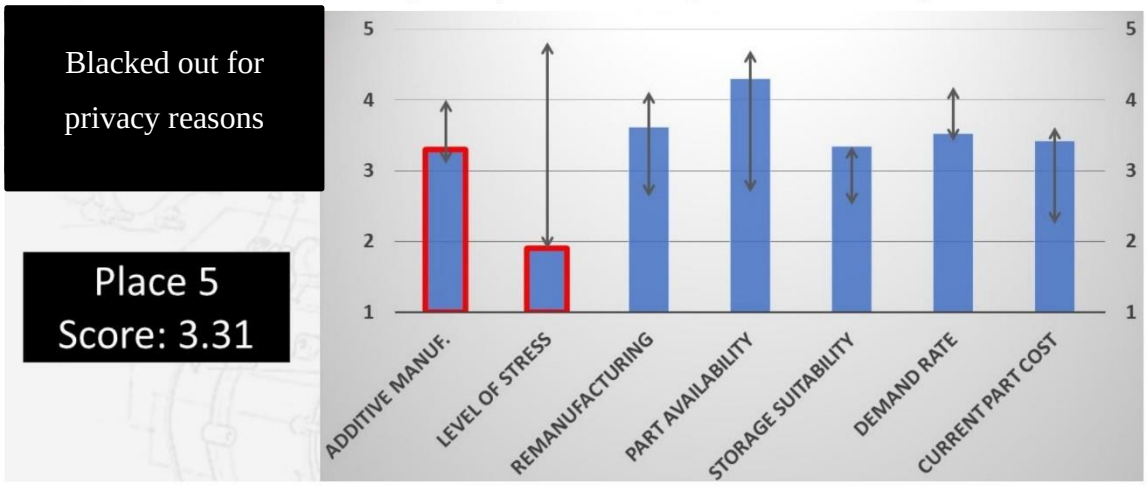
5th Place: Brake Pad

(The higher a score of an attribute, the higher the potential for utilizing Additive Manufacturing)



Do you AGREE with the 5th Place?

◯ Yes
◯ No

Do you AGREE with all ATTRIBUTES SCORES?

◯ Yes
◯ No

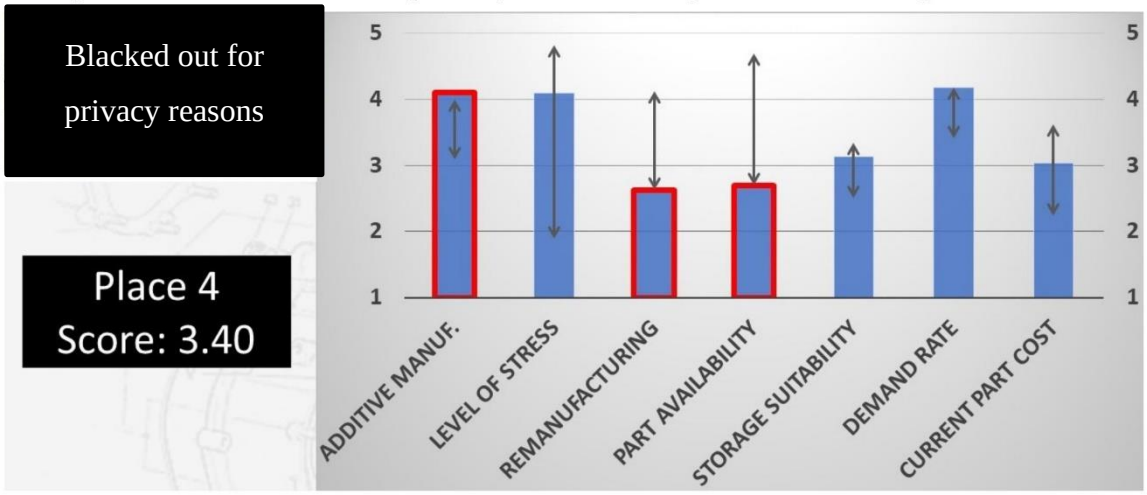
Please provide additional FEEDBACK regarding the outcome of the ranking:

Different place of this part? Different scores of attributes? Additional feedback?

_____

4th Place: Air Vents

(The higher a score of an attribute, the higher the potential for utilizing Additive Manufacturing)



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Do you AGREE with the 4th Place?	◯ Yes ◯ No
Do you AGREE with all ATTRIBUTES SCORES?	◯ Yes ◯ No
Please provide additional FEEDBACK regarding the outcome of the ranking: Different place of this part? Different scores of attributes? Additional feedback?	_____

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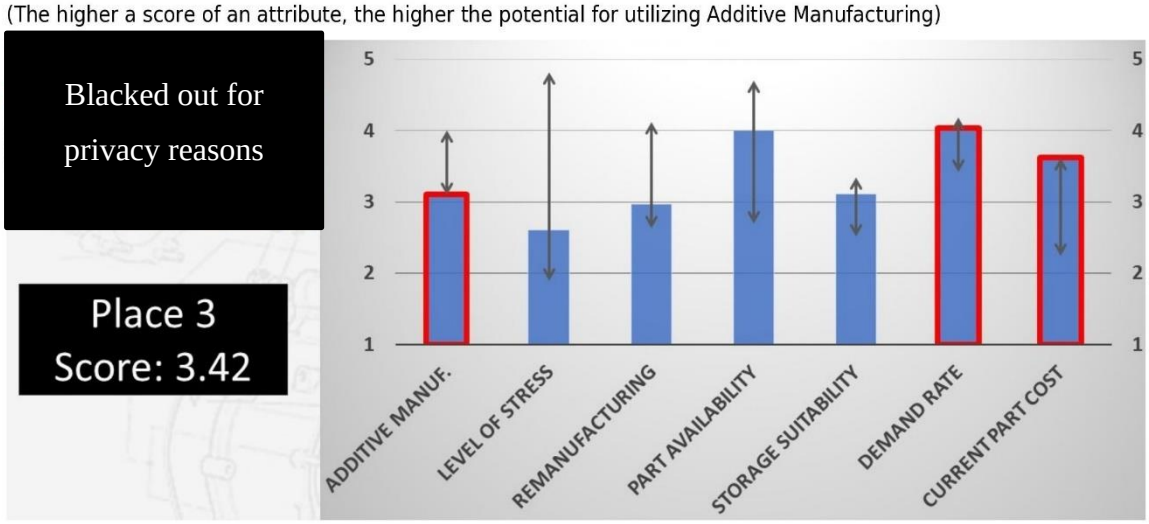
Places 3 to 1

Explanation of the SCORING of ATTRIBUTES:

High Score for ADDITIVE MANUFACTURING if Suitability for AM is good. High Score for LEVEL OF STRESS if Level of Stress is Low, which is good for AM. High Score for REMANUFACTURING if Remanufacture with Conventional Production Methods is Difficult which is a Potential for AM. High Score for PART AVAILABILITY if the part is not available, which is a potential for AM. High Score for STORAGE SUITABILITY if Storage Suitability is Low, which is a potential for On-Demand production with AM. High Score for DEMAND RATE if Demand Rate is Low, which is an advantage of AM High Score for CURRENT PART COSTS if Current Part Costs are High, which is a potential for AM to reduce costs.

3th Place: Exhaust Manifold

(The higher a score of an attribute, the higher the potential for utilizing Additive Manufacturing)



Do you AGREE with the 3th Place?

◯ Yes
◯ No

Do you AGREE with all ATTRIBUTES SCORES?

◯ Yes
◯ No

Please provide additional FEEDBACK regarding the outcome of the ranking:

Different place of this part? Different scores of attributes? Additional feedback?

_____

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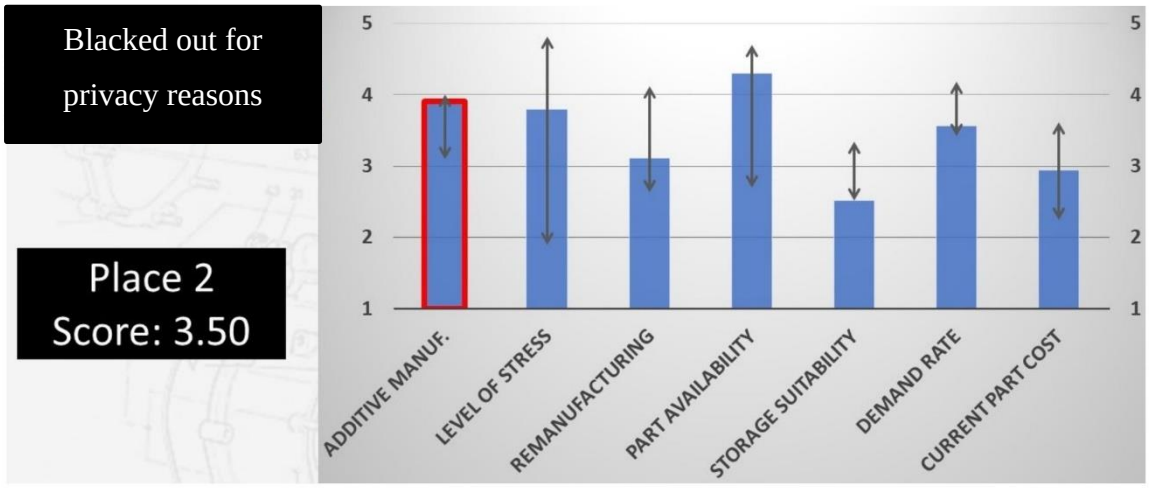
2th Place: Interior Knob

(The higher a score of an attribute, the higher the potential for utilizing Additive Manufacturing)



Do you AGREE with the 2th Place?

◯ Yes
◯ No

Do you AGREE with all ATTRIBUTES SCORES?

◯ Yes
◯ No

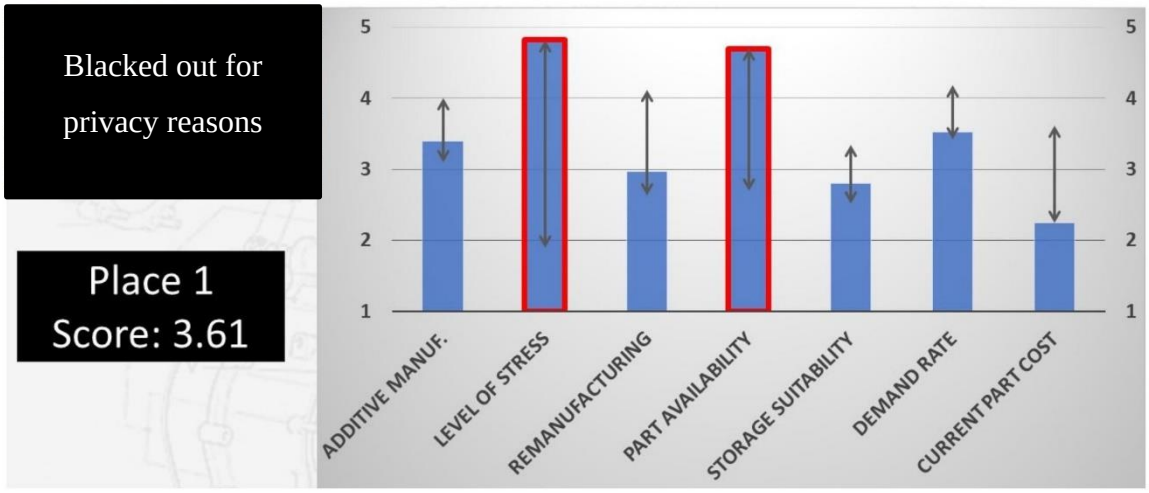
Please provide additional FEEDBACK regarding the outcome of the ranking:

Different place of this part? Different scores of attributes? Additional feedback?

_____

1th Place: Badge

(The higher a score of an attribute, the higher the potential for utilizing Additive Manufacturing)



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Do you AGREE with the 1th Place?	◯ Yes ◯ No
Do you AGREE with all ATTRIBUTES SCORES?	◯ Yes ◯ No
Please provide additional FEEDBACK regarding the outcome of the ranking: Different place of this part? Different scores of attributes? Additional feedback?	_____

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Genaral Feedback

This is the last survey of the Delphi-process. If you have any further FEEDBACK you would like to provide, please write in comment box

_____