THE INFLUENCE OF PRODUCT LIFETIME ON REMANUFACTURING OF VEHICLE COMPONENTS

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Abstract: *Improving the component quality of vehicles, machinery and equipment eliminates the need for remanufacturing of these components. In the article, we discuss the possible failure of vehicle components in product lifetime and the relation to remanufacturing. We tried to find an answer to the basic question of what influence has the development of the lifecycle of passenger cars and the changes of the main failure components on the need for remanufacturing. Statistical data as demographic, vehicle population and vehicle failure rates have been applied. In addition, the failure probabilities of cars and their components were determined. Our research shows, that in case the companies (OEM) want to act in an ecologically sensible way, they have two options. First option is, in case the components do not achieve the required service life, the companies should keep them as a guarantee. Second option is to cover 80% of the required components by remanufacturing solutions, whereby the components' price is max. 80% of the new parts' price over a period of up to 15 years after the end of the OEM production must be made available. Electro mobility and autonomous driving can have a positive or negative effect to remanufacturing. Which effect will appear is dependent on fulfillment of requirements of robust design and capable processes according to ISO 26262.*

Keywords: *Passenger Car Lifecycle, Vehicle Component Failure, Remanufacturing, Autonomous Driving, Electro Mobility*

1. INTRODUCTION

Remanufacturing helps to carry out a more sustainable consumption of natural resources and to reduce associated environmental damage. Remanufacturing also mitigates the growing risks for the economy due to higher material costs and supply bottlenecks and downtimes. The changes in recent years, such as quality improvement of passenger cars (PKW), electromobility or autonomous driving must be repeatedly assessed relating to the impact on remanufacturing.

The objective of the article is to evaluate the development in the lifetime of passenger cars in recent years, to identify the main failure components and finally to describe the influence on remanufacturing. In order to accomplish this objective, the following questions are to be answered:

- What is the development of the lifecycle of passenger cars in recent years?
- What are the main failure components and the relation to remanufacturing?
- What influence has the development of the lifecycle of passenger cars and the changes of the main failure components on the need for remanufacturing?

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2. RESEARCH METHODS

Research methods in the sciences procedures and analysis techniques are designate and serve to clarify scientific questions. Especially in the social sciences, the distinction between quantitative research methods and qualitative research methods is familiar. "The empirical methods are, in the broadest sense, experiential procedures. The word empiric comes from the Greek word "empeiria" and means something like "experience" "[16].

The quantitative methods in empirical social research include all approaches to the numerical representation of empirical facts, but also to support the conclusions of the empirical findings with tools of inferential statistics [10]. Quantitative methods include sample selection, data collection and analysis. Thus, empirical results, as presented in this work, represent causal relationships that relate to years of experience and in a correlation represent the issues of failures and remanufacturing of vehicle components. As [10] suggests, causal relationships should be "carefully described, ordered and quantified", which is the case in this article.

The following research methods are used in the article:

- Application of statistical methods used in the evaluation of development of population, vehicle population and vehicle failure rates. In addition, the failure probabilities of various components were determined or assessed.
- The qualitative literature research provides a solid foundation with the latest and groundbreaking studies on remanufacturing, and thus a better understanding of what is already known about this topic.
- Empirical data has been collected over the past 5 years through interviews and discussions with customers and employees in Bosch Company. In doing so, it was possible to record objective facts and also to record opinions and attitudes. There are possible disadvantages, e.g. only verbal information were given.

3. PRODUCT LIFE-CYCLE MANAGEMENT

Production is also referred to as manufacturing or processing, especially of items. In legal linguistic usage, manufacturing is the process of transformation effected by man's work, which produces products (economic goods) or commodities from natural as well as already produced raw materials, using energy and certain means of production that can be stored.

The term production refers to the production of goods in general. Goods are generally divided into primary production (primary sector of the economy), i.e. production of assets from natural resources and the production of goods.

The terms manufacturing or fabrication are limited to craft and industrial goods and merchandise.

Many terms, such as value chain, shop-floor chain, transport chain or supply chain are used in the literature as synonyms. The value chain thus includes the components of logistics, production and information.

Product Life Cycle Management (PLCM) refers to a strategic approach to managing products throughout their product lifecycle, which must be implemented on a business-to-business basis through appropriate technical and organizational rules. With its interdisciplinary approach, it is a key success factor for the conception and realization of cost-optimized and customer-specific products and solutions for both original equipment as well as spare parts [11].

At the same time, it forms the interface for all areas of product management and for the need of spare parts for timely securing post-series supply and failure management. As can be seen from the Figure 1, the remanufacturing platforms are already being developed in the series phase (two to three years after the start of production). The foundations have already been laid by means of a remanufacturing concept in the development phase. The timing of the spare parts requirement is very much dependent on the quality of the components and thus on the failure rate of the products. Several thousand vehicle components were used for the analysis. The result of the analysis shows that most products fail in significant quantities until 5-8 years, and the need is high enough to make remanufacturing meaningful. Early failures detected in the first 4 years can be provided more economically by the series parts.

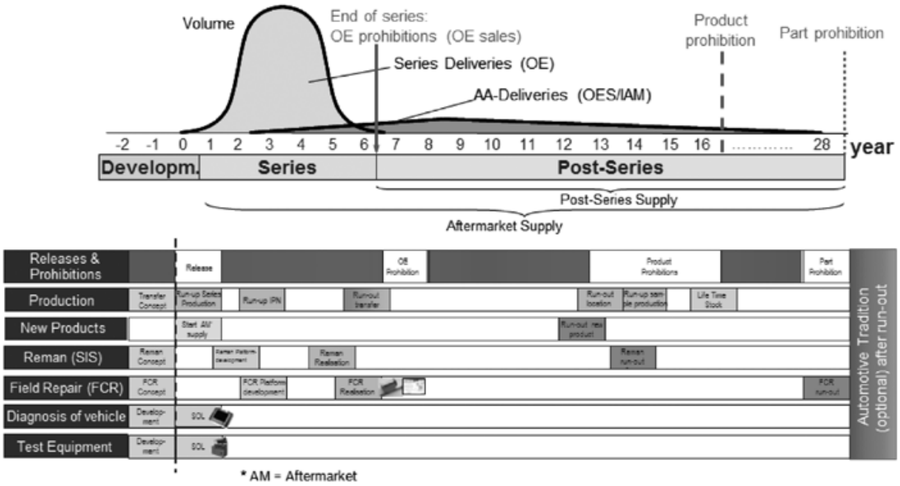

Figure 1: Product Life-Cycle Management [11]

Whether there is a need for remanufacturing components or not depends on two essential parameters. First, the lifecycle of the vehicles and second, the lifecycle of the components used in the vehicle. If the lifecycle of a vehicle is less than that of its components, then there will be no need for spare parts components. If the lifecycle of a vehicle is longer than that of its components, then there will be a need for spare parts components that must be covered by either new parts or remanufactured parts. Therefore, in the following parts of this article, the lifecycle of cars is analyzed and evaluated.

2.1 Description of the failure rate

The failure rate is a parameter for the reliability of an object. It indicates how many objects fail on average over a period of time. It is given in 1 / time, i.e. failure per period. A special failure rate unit is Failure In Time (FIT) with the unit failures per 10^9 hours.

When considering a car as a system, the failure of one system part (engine, transmission, brake, ...) can turn off the entire system. A failure is decisive for the system failure. The weakest chain link determines the strength of the entire chain.

A typical failure rate, as seen in many technical applications, has the form of a bath-tube, which is why this curve is called the „bath-tube curve" [8]. The Weibull distribution is a special form of distribution that can be used to statistically assess failure probabilities in systems.

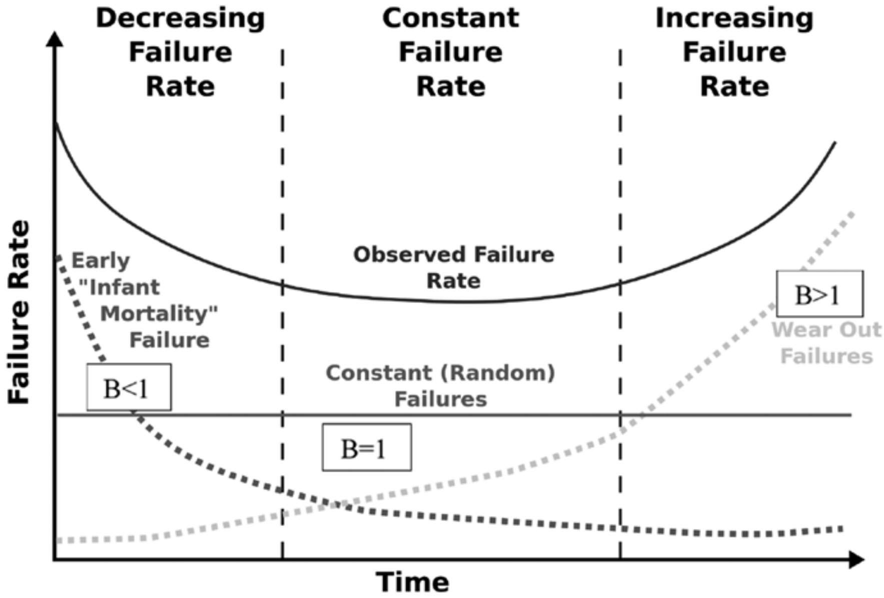

Figure 2: Failure rate depending on the shape parameter [14]

The bath-tube curve can be used to describe the failure behavior in three phases of this curve, the shape parameter B can be used to model whether early or late failures occur more frequently:

- Early failures: decrease with increasing lifecycle
  - can be caused by production errors
  - the failure rate decreases randomly
  - Example: Soft solder joints, which are cold solder joints due to a lack of soldering flux, have in fact contact during putting into service, but loose contact after a short time (no/sometimes contact)
  - B < 1
- Random failures: Constant lifecycle
  - there is almost no wear
  - the failure rate is constant over lifecycle
  - Example: the total failure of a new, running-up car (scrap ready) occurs only as a result of an accident
  - B = 1
- Late failures: Wear failures
  - increase with increasing lifecycle, it comes to increasing aging wear
  - the failure rate increases again
  - wear of carbon brushes in starters, regulators, bearing wear, etc.
  - B>1

The failure rates of components are already very low as a result of the quality progress made in recent years and will be significantly reduced in the coming years due to the requirements of ISO 26262 [8]. According to [5] and Automotive Safety Integrity Level (ASIL) classification the following failure probabilities are recommended:

- ASIL A: probability of failure less than 10^{-6} /hour, equivalent to a rate of 1000 FIT
- ASIL B: probability of failure less than 10^{-7} /hour, equivalent to a rate of 100 FIT
- ASIL C: probability of failure less than 10^{-7} /hour, equivalent to a rate of 100 FIT
- ASIL D: probability of failure less than 10^{-9} /hour, equivalent to a rate of 1 FIT

3. WHAT IS THE DEVELOPMENT OF PASSENGER CAR LIFECYCLE IN RECENT YEARS?

Before answering the question as to how the development of the lifecycle of passenger cars has been in recent years, the question must be answered as what was the development of vehicle demand in Germany.

3.1 Development of vehicle demand in Germany

The population in Germany has been stable in recent years with about 81 million people. With this stable population, the number of registrations was the answer to the economic and political factors with an average of 3.2 million vehicles each year. This corresponds to an annual rate of 4% new vehicle registrations and means an average car lifecycle of approximately 14.5 years. With this fleet Germany alone has about 46.5 million vehicles, which must be driven, maintained and scrapped at the end of its lifecycle [9].

Table 1: New registrations in Germany [15]

Number of new vehicle registrations in Germany from **2007 to 2017 (in millions)**											
Year	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007
Number in millions	3,44	3,35	3,21	3,04	2,95	3,08	3,17	2,92	3,81	3,09	3,15

3.2 Assessment of „e-mobility” and „autonomous driving“

The technological changes in the vehicle market have been very rapid in recent years. Currently, two topics are very dominant and also discussed very controversially. The following questions are to be evaluated in the article context:

- What development will electric and hybrid vehicles make over the next few years?
- Will autonomous driving noticeably reduce the number of vehicles in the streets?

As can be seen from Figure 3, the global car population of cars will still increase from 911 million in 2016 to 1,124 million. During this period, both the useful lifecycle of the cars and the annual production volume from 73 million in 2016 to 81 million will increase. The average rate of increase between 2016 and 2024, at 1.7%, is slightly lower than that for 2010-2024 at 2.4%.

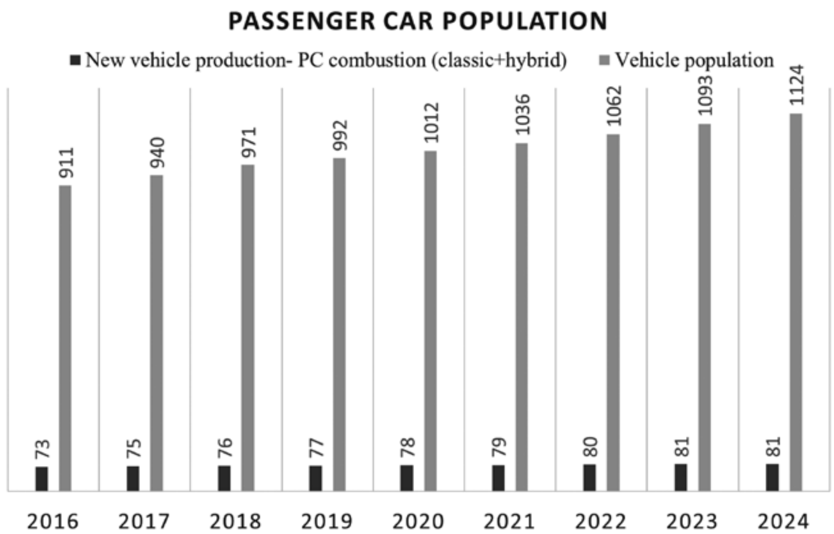

Figure 3: Passenger Car Population [12]

From the passenger car population (Figure 4), the vehicles relevant to Bosch (approx. 95 million to 115 million) were determined and assigned to the respective categories. From this it can be seen that the share of electric vehicles (EV) will increase to about 8% by 2024. At 21%, the number of hybrid vehicles will be much stronger than that of electric vehicles. This means that in 2024 Bosch vehicles that are still relevant will still be equipped with combustion engines. More importantly, these technical changes will not have a negative impact on the series repair of vehicles, since the electric motors are technologically similar to starters and generators, and thus the series repair of electric vehicles will have a positive contribution to the ecology and macroeconomics.

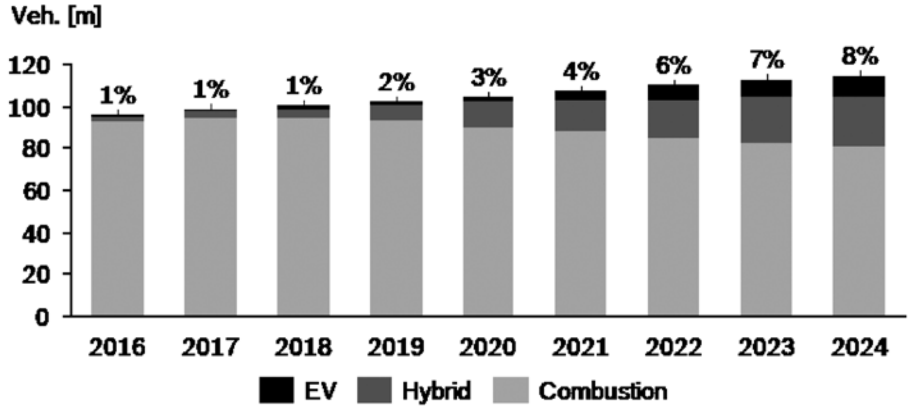

Figure 4: Distribution of vehicles in EV, hybrid and combustion [12]

3.3 Service lifecycle of passenger cars in Germany

On 1 January 2018, approximately 46.5 million cars were registered in Germany. Of these, about 13.5% are under 2 years, about 17% between 2 to 4 years and about 28.6% (13.3 million) between 5 and 9 years. Thus, in total about 59% of passenger cars are younger than 10 years old [9]. Thus, about 41% of the cars are 10 years or older and thus very interesting for the remanufacturing market.

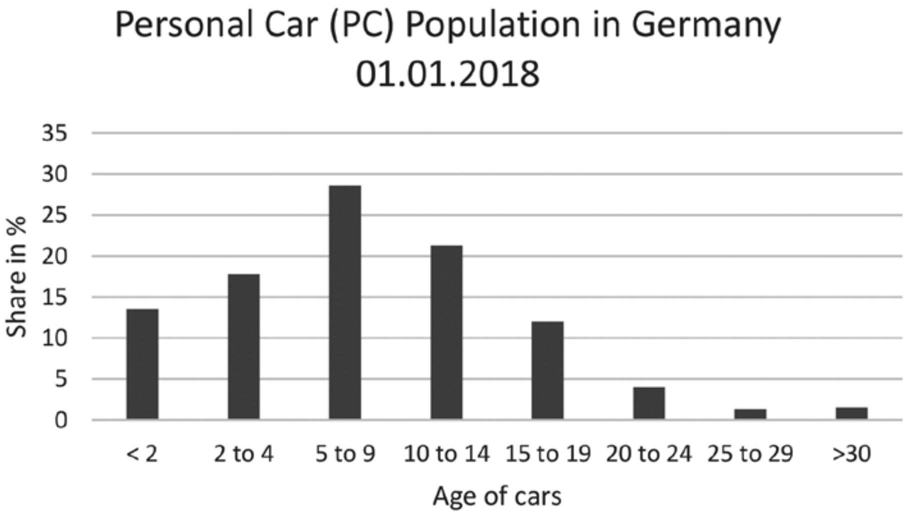

Figure 5: Stock of passenger cars [12]

The average age of the registered passenger cars was 9.4 years and has therefore risen again compared to the previous year (9.3 years). There are several reasons for the outlined development:

- First and foremost, of course, is the technical progress that has successively led to a longer „durability" of new cars. This applies e.g. for bodywork (improved rust protection) or engine and transmission technology. They allow a longer service lifecycle and mileage of the car. Thanks to this improved vehicle quality, motorists can increasingly delay the purchase of a new car.

- Another reason for the rising average age of car stocks is also the higher list prices for new cars. This price increase is likely to cause many private car buyers to use their cars longer and to accept also in older cars repair and maintenance costs. The striking growth in average new car prices is due to the fact that the share of commercial customers in new passenger car registrations in Germany has risen in recent years. Many commercial customers are more likely than private car buyers to purchase better-equipped and therefore higher priced cars. If these cars come after a certain time on the secondary market, they are for many private customers a lucrative alternative to buying new cars.
- A sensible alternative to regulate the CO2 emissions of road traffic would also be in addition to the reduced cars‘ usage the use of remanufactured products.

3.4 Lifecycle of cars in USA

For years, quality statistics on the quality of vehicles (cars, commercial vehicles) are maintained and updated annually. The general trend of the complaint rates is declining. As can be seen from the study of June 17th, 2010, the vehicles (cars, commercial vehicles) in 1999 caused, depending on the manufacturer, European and Asian vehicles 150 problems and the US 177 problems related to 100 vehicles. These values have steadily declined in recent years. In 2010, the number of problems was only 108 or 109 problems per 100 vehicles [6].

Figure 6: Initial Quality of U.S. and Import Brands, 1999-2010 [6]

Vehicle manufacturers, whether they are from the US, Europe or Pacific Asia, have been able to reduce the initial errors, although in the past 10 to 15 years the complexity of vehicles has increased significantly.

In addition, the quality requirements of customers are constantly increasing, so that the warranty periods have been increased in recent years from 2 to approximately 7 years. Car manufacturers have huge budgets for the design, engineering, production and marketing of new models and are mastering these initiatives with improved quality rates in the field.

Having a strong quality image is necessary for automakers to be able to compete in the market today, both in the United States and globally. The initial quality is the first indication of how the vehicles will behave over their lifetime.

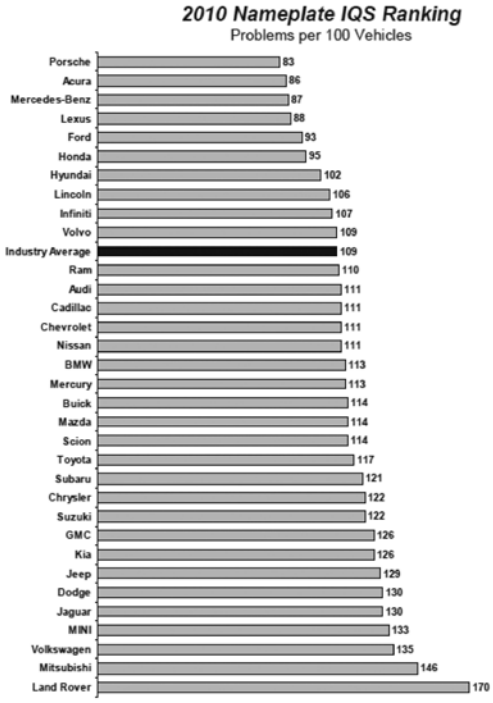

Figure 7: IQS Ranking 2010 [6]

According to [6] we can find the rank order. Ranking is based on numerical scores, and not necessarily on statistical significance, nor as a statistic on quality over the life of vehicles.

The study was also conducted in 2014 and published on June 18th, 2014. It represents the number of problems experienced by owners of a new vehicle, which has increased compared to the previous year. It shows that in recent years, the problems experienced by vehicle owners during the first 90 days of ownership have grown steadily.

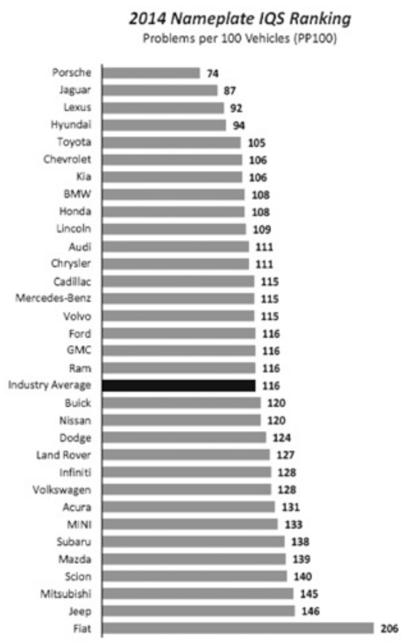

Figure 8: IQS Ranking 2014 [7]

The study shows that the average initial problems in 2014 is 116 PP100 (parts per million), 3% higher than in the previous year, with 113 PP100 initial problems.

The study identifies two primary causes for the increase in 2014:

- Firstly, recently launched vehicles seem to be more problematic than prolonged vehicles. On average, recently launched vehicles undergo 128 PP100s compared to 113 PP100s for extension vehicles. The increase in problems among fully new vehicles is mainly found in the areas of voice recognition, Bluetooth pairing and audio systems. Automobile manufacturers are trying to convince consumers with new vehicle techniques and features without introducing additional quality issues into their vehicles, but these techniques are very difficult to understand and use.
- Second, weather influences have a negative impact on quality. In some areas, increases in problems are due to exacerbations of weather conditions. Consumers in the country's southern and western regions report the same level of problems as in 2013 (114 PP100). In contrast, consumers in the Northeast and Midwest regions report an increase to 117 PP100 in 2014, compared to 112 PP100 in 2013. The majority of this increase is found in the HAVAC (heating/air ventilation/air conditioning), Exterior and Engine / Transmission categories in which hard weather conditions have a detrimental effect on vehicles. Although the car manufacturers are testing the vehicles under „worst-case conditions", it is impossible to completely avoid the effects of the severe weather.

4. WHAT ARE THE MAIN FAILURE COMPONENTS AND THE RELATION TO REMANUFACTURING?

The longevity of cars causes more components wear out during their lifecycle as it was planned or even not planned as the useful lifecycle of the cars is higher than they are designed. For younger cars (0 to about 5 years), the wearing parts are usually replaced expertly in the car service centers within the regular maintenance intervals. For these cars, customers either have warranty claims or warranty agreements that ensure the timely replacement of components. For the cars older than 5 years, a preventive exchange is rather not carried out and thus these cars fall under the breakdown statistics. With age, the risk of breakdown increases. According to [1], "the likelihood of a three-year-old car is still 1.7%, it rises to 7.1% after 13 years. Only from the Youngtimer age (20 years), the number of breakdowns decreases again, because the old sweethearts are better maintained and driven less" [1].

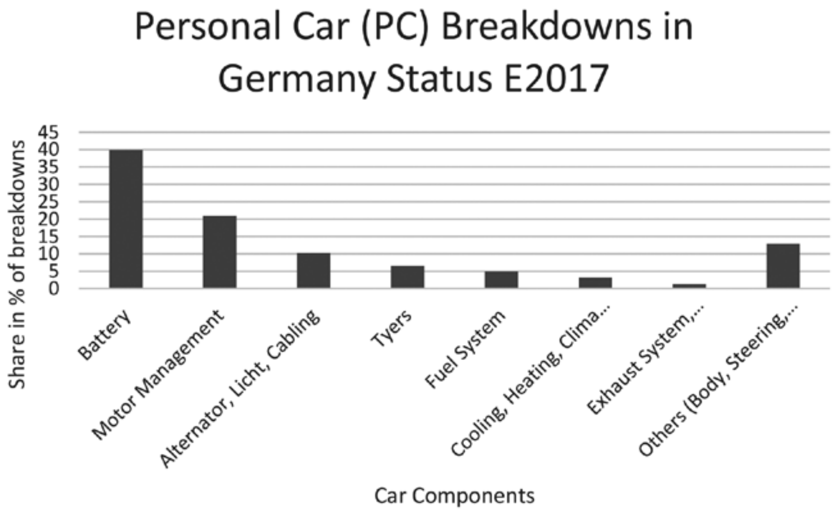

Figure 9: Distribution of defective passenger car components [9]

As shown in the figure above, the battery (conventional) accounts for around 40% of the main cause of these breakdowns [4]. If one compares these values with the ADAC vehicle statistics of 2012, electrics in general (battery with 31.7% and alternator and starter with 12.3%) accounted for 44% [4]. The increase of approximately 8.3% is certainly due to the increased demand on the batteries (e.g. start / stop systems, larger number of consumers) and the aging vehicle fleet. Another reason for these failures is "the increasing complexity and interconnectedness of vehicle-mounted electronic components and with them associated ever-increasing share of software" [4]. Unfortunately, it should be noted here that the battery currently has no remanufacturing options and therefore this market can only be served by new batteries. With a share of around 20%, engine and engine management come second in the breakdown statistics. These problems are primarily software bugs that can be fixed by updating or replacing the electronic components. Only in third place with approx. 10.2% are the starters, generators incl. lighting and wiring in the breakdown statistics. It is only worthwhile for starters and generators to use a remanufactured product due to the high quality of the components [2].

5. WHAT INFLUENCE DOES THE DEVELOPMENT OF THE LIFECYCLE OF PASSENGER CARS AND WHICH CHANGES IN THE MAIN FAILURE COMPONENTS HAVE ON THE NEED FOR REMANUFACTURING?

The analysis of the development of the service lifecycle in Germany and in the USA of passenger cars shows the following results:

- Remanufacturing is only required if the lifetime of the used components is less than the expected useful life of the vehicles, machines and systems. The responsibility for the failures during the expected useful life lies essentially with the producer and, to a lesser extent, the user. The failures can be differentiated as follows:
  - Failures caused by users (accidents or incorrect use)
  - Failures caused by the producer due to non-robust design or unstable and uncapable processes in the value chain.
- The passenger cars on Germany's roads are getting older. Since the beginning of the millennium, the average age of the passenger car fleet in Germany has increased almost steadily. In 2000, a car in existence was still around seven years old on average. By the beginning of 2015, this number had increased to nine years, setting a new record. Only at the beginning of 2010 – i.e. directly after the scrapping premium of 2009, when around 2 million older cars were scrapped and replaced by new or only year or several years old cars – did the average age of the vehicle fleet drop slightly [9].
- The technological advances that are gradually leading to longer component durability due to more robust design and stable and capable manufacturing processes, reduces the need for remanufactured components.
- Increased requirements on better technology according to IATF 16949 and ISO 26262 for further improvement of components lead to the reduction in remanufacturing demand:
  - An average car today consists of up to 10,000 components. Of course, depending on the size and equipment of the vehicle, this number can be more or less.
  - In the worst case scenario, if all 10,000 components had an ASIL A-rating and therefore a failure probability of 10^{-6} failures / hour, the overall system of passenger cars would have a probability of failure of (10,000 components × 10^{-6} failures / hour) = 10^{-2} failures / hour. Since a car is operated for approximately 4,000 hours over the lifetime, this would mean a failure of 40 components over the life of a car.
  - In the best case, if all 10,000 components had an ASIL D-rating and thus a failure probability of 10^{-9} failures / hour, the overall system of passenger cars would have a

failure probability of (10,000 components × 10^{-9} failures / hour) = 10^{-5} failures / hour. Since a car is operated for approximately 4,000 hours over its lifetime, this would mean a failure of 0.40 components over the life of a car.

- The longevity of cars causes the structures in the vehicle fleet change only slowly. Therefore, it will take many years for cars with alternative drive technologies (electric, hybrid, hydrogen) to play a significant role in the German passenger car fleet. The future vision of a largely climate-neutral or locally emission-free German road traffic until 2050 is hardly achievable from today's perspective.
- The increased warranty periods (up to 7 years) show the quality enhancement of the components and cause the components to be replaced with new parts by OEMs as a guarantee or goodwill in the scheduled maintenance. This also reduces the need for remanufacturing of components.
- Alternative drive technologies lead to the exchange and thus the rejuvenation of cars. See the scrapping premium in 2008/2009 and its impact on the vehicle fleet in Germany [13]. Remanufacturing can no longer be economically viable for older cars. On the other hand, shorter warranty periods for electric vehicles could offer additional potential for remanufacturing [3].

6. RECOMMENDATIONS

The result of this article and, thus, management recommendations are:

- The reliability analysis of the lifetime of vehicles must be fully implemented and also made available transparent analogously to the ADAC breakdown statistics.
- Improvement of the component quality of vehicles, machinery and equipment eliminates the need for remanufactured products. In order for the companies (OEM) to act in an ecologically sensible way, they should be worn as a guarantee if they do not reach the required service lifecycle or they must cover 80% of the required components by remanufacturing solutions, whereby the components' price is max. 80% of the new parts' price over a period of up to 15 years after the end of the OEM production must be made available.
- Both requirements can only be met by legislation at national, European or international level. With the existing laws, the companies (OEM) far too early (1 to 2 years under the warranty / guarantee) are loosen from the responsibility.
- Electromobility and autonomous driving make the cars more complex and thus increase the risk of many early outages (children's diseases) and thus increase the need for remanufacturing solutions.
- Due to the higher requirements of IATF 16946, ISO 26262 and the imminent change in electromobility and autonomous driving, the need for remanufacturing can be further at risk in the future. However, these influences can only be expected in the next 5-8 years.

7. CONCLUSION

Whether these theoretical assumptions and management recommendations can actually be implemented depends on many factors:

- The informative value of the data available for this article is essentially attributable to the breakdown statistics from Germany and the USA. There are no exhaustive reliability data from OEM or other institutions, such as the reliability of the vehicles over the

lifetime. Therefore, the required management recommendations have an uncertainty that needs to be considered when considering the topic further.
- How will consumer behavior change? So the observer must ask how important to him is the reliability of passenger cars. Looking at the development of recent years, the quality requirements of the customers have increased and the vehicle manufacturers have responded to them and permanently improved the vehicle quality.
- If the laws and regulations are tightened at the national, European or international level, analogously to the requirements for the recycling of plastics, end-of-life vehicles, etc., this also applies to the reliability and warranty of vehicles and these requirements for reliability are implemented by the vehicle manufacturers.
- How the vehicles are designed and built by the changes and the increased demands of electromobility and autonomous driving that will have an influence on the reliability and the sophisticated vehicles can actually fully implement the higher requirements by IATF 16946, ISO 26262.

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