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Article

A Study on Additive Manufacturing of Metal Components for Mobility in the Area of After-Sales with Spare and Performance Parts

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Abstract: Mobility is undergoing changes. Increasingly strict legislation regarding pollutant emissions and the protection of the environment are more important than ever. The change to electric mobility is also presenting the mobile world with new challenges and opportunities. Vehicles are becoming more and more efficient with higher power densities and better performance. Application-adapted components are being developed and used as a matter of preference. New production technologies can help to realise the change in mobility reliably. Additive manufacturing is one way of producing functionally integrated and performance-optimised components. AM offers the possibility to produce application-specific performance parts. Electric vehicles often have a problem with the thermal load of the components during power output and charging. Additively manufactured components with optimised topology and integrated cooling strive to achieve higher power density, enhanced cooling performance, and improved mechanical properties. AM not only makes it possible to produce functionally integrated and application-adapted components but also to reduce CO_2 emissions and conserve resources. The potential of additive manufacturing for mobility is particularly interesting for the spare and performance parts sector. Components can be improved in performance and manufactured directly on-site. The higher power density and the elimination of transport routes can make an additional significant contribution to environmental protection. This paper presents an overview of the current state of additive manufacturing in the field of electromobility with regard to replacement and performance parts using 3D metal printing. Based on an extensive literature research, a market overview is given. This serves as the basis for the further procedure and, building on this, the advantages of additive manufacturing are demonstrated using the example of an electric motor. The selected electric motor is an example of a defective component in a vehicle that needs to be replaced and whose performance can be improved by additive manufacturing and which can be produced on-site in a quantity of one. The motor is verified by means of a FEM simulation in order to determine the selection of an optimal water jacket topology and to demonstrate further potential for the future.

Keywords: after-sales; spare parts; performance parts; resources efficient; 3D metal printing; higher power density; topology optimised; CO_2 reduction

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1. Introduction

With increased service orientation and product innovation, the aftersales market has gained significantly in the global market. In 2018, Germany's automotive aftermarket was worth USD 21.5 billion and it is predicted to grow at a compound annual growth rate (CAGR) of 1.1% between 2019 and 2025 [1]. The following products are some of the aftermarket products that are examined primarily for a product innovation strategy: high-capacity engines, electric motors, batteries, lights, and electronic components. To facilitate safe, sustainable transportation, manufacturers and suppliers provide innovative solutions. Plug-in electric car sales have surged globally in recent years as a result of the automotive industry's move to e-mobility and sustainability. A conventional vehicle typically contains over 2000 components, whereas an electric vehicle includes significantly fewer components. Since the drivetrain is a fundamental component of an automotive, manufacturers will mainly focus on making the parts associated with the drivetrain first. It is expected that the number of parts will fluctuate throughout the forecast period as some companies will devote some of their resources to the creation of EV parts and components. Power inverters, (direct current) DC–DC converters, battery parts, and electrical motor control units are some of the other crucial parts that companies will create in order to remain competitive in the market [2]. The adoption of EV-related spare parts in the aftermarket will be gradual at first but with the sector experiencing a paradigm shift, the rate is predicted to increase significantly within a few years [1]. Automotive companies deal with a number of challenges but the most pressing factors relate to the manufacturing, supply, and storage of spare parts, as shown in Figure 1a. One of the most common issues is the cost of ordering spare components. In order to lower the cost per part, conventional manufacturing creates parts in large quantities. The recent ongoing COVID-19 pandemic has also impacted the spare parts supply chain industry to a large extent globally leaving industries to look at alternate directions [3]. Long lead times are another challenge which is associated with traditional spare part productions. If a customer on the other side of the world needs a spare part, ordering, and shipping it can often take weeks, which negatively impacts his or her satisfaction. Sometimes manufacturers decide to discontinue producing certain spare parts altogether, leaving their consumers without options. Instead of this, an advanced reverse engineering process may be used to convert traditionally manufactured spare parts into AM parts that can be produced on demand if needed. In the modern era, as seen in Figure 1b, 3D printing and digital spare parts management have helped address a lot of these issues. With regard to the "VBER" guidelines, the spare parts distribution management is seen to be complex. Since the market and the buyer–seller construct can be very complex, the authors have decided to present a simplified but meaningful form of spare parts supply chain behaviour for additive parts [3–7].

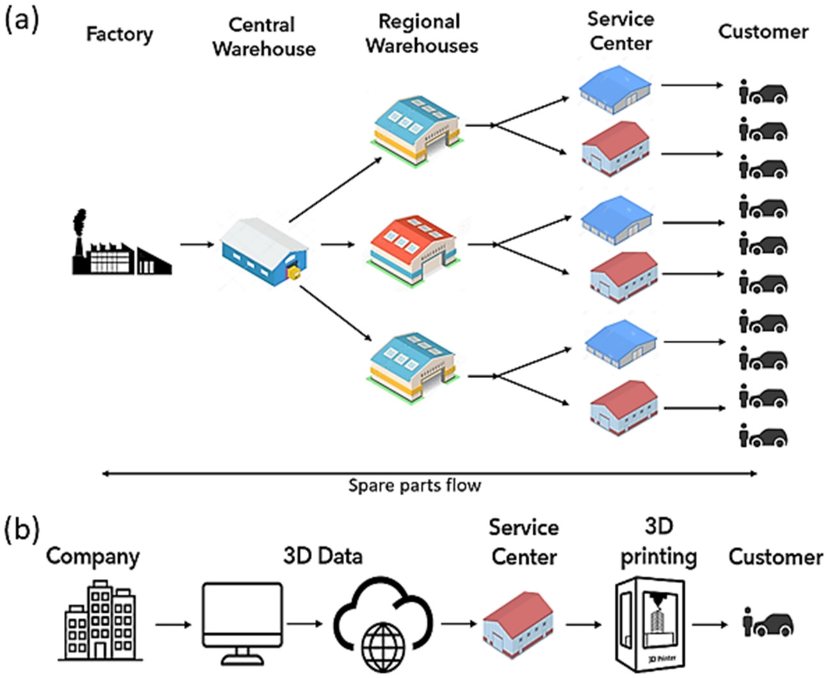

Figure 1. (**a**) Spare part flow chain structure, (**b**) Digital spare parts management.

2. Materials and Methods

In order to discuss how additive metallic spare parts are already being used in the automotive environment but also to show the potential that arises from additive manufacturing, this study will on the one hand provide a literary introduction to additive spare parts and their technical characteristics as the state-of-the-art and science, and on the other hand, a conventional component that is already in use will be simplified and provided with the advantages of an additive component, and the potential that arises from additive manufacturing will be shown with an introductory simulation. This component is intended as an example of a performance spare part, which is partially improved and installed as a replacement for a damaged original component. Figure 2 illustrates the theoretical research procedure.

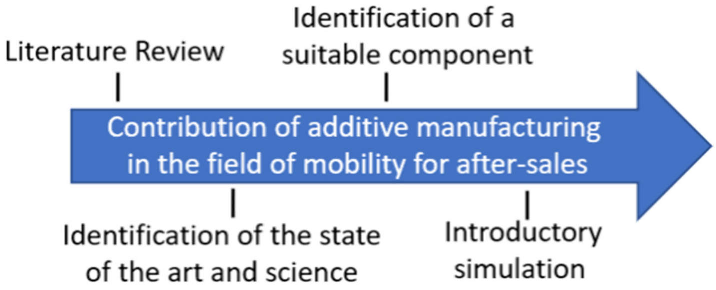

Figure 2. Theoretical research procedure.

For this study, the authors have defined a research question:

"Can additive manufacturing with metal components contribute to more efficient mobility in the form of energy efficiency and environmental friendliness through spare and performance parts?"

The authors have conducted an extensive and detailed literature search. The aim of the research is to discuss a holistic and up-to-date overview of the topic of additive manufacturing of spare parts in the field of mobility.

For this purpose, a literature search was carried out using the Google Scholar database. The authors chose this platform because all other subordinate platforms are also searched. The main topics of additive manufacturing, mobility and spare parts were used for the literature search.

The specific evaluation and search of the literature were followed by the definition of search words that can be assigned to the main topics discussed above. The holistic and systematic literature search is illustrated in Figure 3.

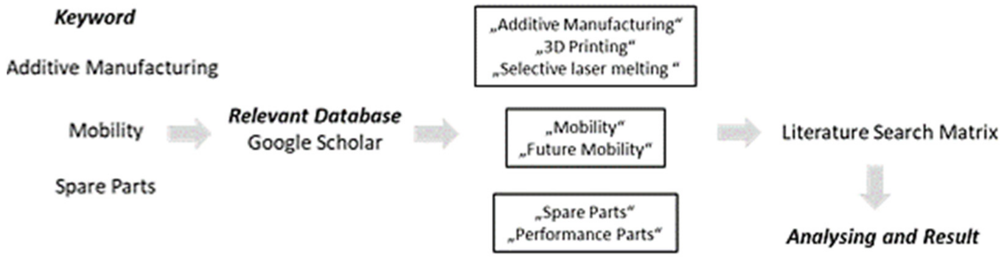

Figure 3. Systematic literature search.

The search words are combined and evaluated in a literature search matrix. As a result, >300 articles were identified and evaluated by looking at the title and abstract. Of these, >185 articles were declared to be suitable and their content was worked through. A classification of the contributions with regard to topicality and scientificity was then carried out. It is striking that more than 65% of the contributions can be described as grey literature and 35% as scientific. After the evaluation with the criteria of topicality, content, the intersection of the main categories, additive manufacturing, mobility and spare parts, contributions > 50 could be declared.

The automotive industry is familiar with additive manufacturing and it is also used there in a focused manner. A large number of different components are already being used and manufactured, whether made of plastic or metal. The authors limit this article to additive manufacturing in the area of metallic components, which can be used for the complete drive train [2,8].

Spare parts industry

It is vital to note that spare parts are frequently a key component in a company's value chain. As a result, the economic performance of the spare parts industry has a broad impact on a company's profitability. A spare part is a part that may be purchased separately to replace an old or broken part of an item of equipment [9]. In general, they are parts that are meant to be readily removed or changed. Spare parts include individual components, sets of components, assemblies or subassemblies, and full products.

Spare parts impact on Industry

Automotive manufacturers rely on aftermarket services for part repair/maintenance, sales of parts and accessories, and so on, bringing together millions of businesses, the majority of which are small- and medium-sized enterprises (SMEs). As a result, COVID-19 has had an impact on the entire ecology of the automotive industry [10]. Initially, the outbreak slowed manufacturing and reduced raw material supply globally, leading export orders to drop and export delays to arise. Supply and demand were significantly impacted due to the continuous spread of COVID-19 throughout the worldwide supply chain. Several factory closures have occurred in key industrial countries as a result of COVID-19 activities such as outside lockdown limitations. Automobiles, electronics, and medicines are just a few industries that have had supply chain issues. As a result, market demand was marked by severe uncertainty and logistical breakdowns made meeting demand unfeasible [11]. For many manufacturing businesses, a global supply chain was established, with enterprises intimately linked to one another. China, the United States, and Germany have emerged as regional industrial hubs for North Asia, North America, and Western Europe, respectively. The export of intermediate products from these nations accounts for more than 40% of total product exports [10]. A number of manufacturing enterprises will be unable to conduct business in the near future due to a scarcity of raw materials and spare components. On the one hand, the United States, China, and Germany have emerged as the most significant production centres for raw materials and spare parts in a variety of sectors; on the other hand, they have emerged as global manufacturing frontrunners [11]. These nations are extremely valuable in industries such as manufacturing, telecommunications, precise instruments, automotive, and others [12].

Centralised Spare parts

The spare parts business accounts for a sizable portion of most companies' total sales. In conventional spare parts industries, spare parts are typically manufactured directly from the beginning of a product, stockpiled, and distributed centrally by the manufacturer. Spare part demand for the future is frequently forecasted and the forecast is frequently backed up by oversized collateral. As a result, the cost of storage and safety stocks is high. When a breakdown occurs, spare components are delivered over long distances to resolve the problem. This philosophy was used in the past and continues to be popular to date [13,14].

In decentralising spare part distribution, we mean getting them to the appropriate places at the right time. There is no necessity that the product's original equipment manufacturer also manufacture spare parts. After ordering the spare part digitally, the buyer can either construct it himself or have it manufactured locally by a third-party manufacturer. AM is the most effective way to establish a decentralised spare parts supply. The only prerequisite for this is a CAD model of the part to be manufactured, in addition to the corresponding part. Because they are decentralised and additively generated, these spare parts are also known as digital spare parts [15]. The fundamental benefit of this decentralised spare parts strategy is that spare parts are always available when they are needed. As a result, reaction times are substantially shortened, and the client is less reliant on a single source, providing them with a broader range of options and allowing them to respond more quickly. Indirect production at the required site also has a lower environmental impact because it eliminates the need for transportation. There are additional benefits for the original equipment manufacturer as the inventory for example can be greatly decreased or eliminated [13,16].

A digital spare part is a concept in which the spare component and related data are electronically sent and preserved. Spare parts are generated utilising 3D printers, which are often positioned close to the end customers. Digital spare parts are now accounted for at least 5% of a company's spare parts market [13,14]. It is possible to employ digital spare parts to boost the productivity of spare parts service organisations while also achieving significant cost savings: spare parts are enhanced, delivery times are lowered, and small batches and individual parts are less expensive to manufacture. A digital spare part, as opposed to a physical spare part, takes up no shelf space in a real warehouse and significantly reduces shipping and delivery times [13]. Digital spare parts also allow for the creation of custom-made parts, which saves costs and labour time. Numerous product versions and improvements may now be produced quickly and affordably thanks to digital manufacturing methods. Similarly, a spare part can be redesigned to be 3D printed, as each manufacturing technology has a unique structure that is cost-effective [17,18]. The digital spare part concept can offer numerous revenue generation options in addition to providing a new manufacturing method for small series production batches or individual parts. Digital spare parts enable new companies to enter the worldwide spare parts industry. Furthermore, like in other digitalised industries, these companies are expected to enter the market. These players will very certainly begin to broker both manufacturing and manufacturing services, changing the entire spare parts sector.

Additive Manufacturing

The terms additive manufacturing (AM) and 3D printing are related to manufacturing processes in which the model is produced in layers from a digital model of a part or assembly. The AM technique is referred to by a variety of names, each of which provides some insight into how the technology was being employed at the time. With rapid prototyping, a variety of tools, tooling inserts, fixtures, assemblies, and jigs are created for larger prototype series [19]. Manufacturing finished goods and parts using rapid manufacturing, or AM has gained considerable traction in recent years. AM is attractive primarily because it allows parts to be manufactured that otherwise would not be possible using traditional subtractive (such as computer numerical control—CNC machines) or formative techniques (such as casting). Design for AM provides engineers with a new tool for creating optimal parts based on certain standards. These standards are usually known as DfAM. When the item is complicated, made of valuable material, or the product is no longer available through existing distribution sources, AM can be a more cost-effective technique for generating components [20].

Design for Additive Manufacturing (DfAM)

Traditional manufacturing is constrained by several design constraints. AM, however, offers many principles that can be exploited due to this design freedom. Multiple parts can be combined into one as part of these principles, performance is increased by constructing complex internal geometry, weight is decreased by removing surplus material, and topology optimisation can be utilised to automate some of these operations. It is possible to implement DfAM in a few ways, ranging from the quickest to the most challenging. One of the simplest ways to construct an AM model is to just duplicate an existing design with no modifications. It is beneficial when a single element is very complex and hence difficult to create using standard methods, as well as when employing expensive materials that require little waste. It is also advantageous when a product lead time is unusually long or if the parts are no longer manufactured [21].

Second, using the DfAM rules to redesign a single component, either to enhance performance or weight by employing design optimisation approaches or to improve the component's AM applicability. It can then be made lighter, less expensive, or stronger than the original part while still allowing for direct replacement. The assemblies are modified through this process, as well as tested and evaluated, the aim of this process is to reduce the manufacturing risks associated with production technology [21,22]. The third scenario is part combination, which decreases part count, lowers assembly costs, and enhances performance. It occurs when a firm or individual feels at ease with DfAM and has shown its worth with individual components. When parts are merged, assembly and part prices can be decreased, inventory and weight can be reduced, and performance can be increased. As a result, the GE Leap fuel nozzle went into mass production. Despite the fact that only the tip is made using AM and the rest of the component is cast with minimum post-processing, it looks and operates quite similarly to the original. Furthermore, it is compatible with existing assemblies while providing the previously described benefits [23]. The fourth scenario involves a comprehensive rethinking of the overall assembly and redesign based on core principles and design needs analysis. Even though this technique requires a significant amount of time and work, AM has the potential to significantly revolutionise and disrupt a variety of sectors [24]. In the future, the spare parts industries could be transformed by combining DfAMs, LPBFs, and characterised AMs. Now it is possible to create new families of electrical machines, brackets, and integrated parts that were not possible using traditional methods. This research will fill some of the existing gaps and inspire the adoption of AM with spare parts. Some researchers have already begun to investigate aspects of AM with spare parts but they have not yet combined them all [25].

Additive Manufacturing and its Potential

AM is a cutting-edge technology that offers numerous potentials for businesses to boost manufacturing efficiency by opening up new channels. Within the next decade, AM has the potential to replace existing approaches and become the standard. To remain competitive in the modern manufacturing business, items should be designed and made with two opposing goals in mind: reducing time and cost while enhancing quality and adaptability. The following are some of AM's potential.

- Part consolidation: The reduced part count is an effective way to reduce the time and costs associated with manufacturing. AM is unique in its ability to manufacture complex geometries that cannot be manufactured with conventional methods. A mechanical assembly would normally have several pieces created as separate components but maybe additively manufactured as a single unit despite the geometry being complex [26].
- Lightweight design: By using AM technology, lightweight structures can be designed and manufactured where conventional manufacturing processes are ineffective. For most components, extra material in conventional production can be removed during the design process. A lightweight, high-strength part is produced when a material is applied only where the function requires it. Over the lifecycle of a part, every gram of material saved can generate substantial cost savings while also protecting the environment [27].
- Freedom of design: The design freedom provided by AM allows engineers to consider options that would otherwise be limited. Another design flexibility is the ability to create structures with varying porosities. Complex geometries with overhangs/undercuts and internal spaces, lighter hollow or half-open mesh, and honeycomb structures that are lighter and use fewer materials are among the new possibilities. Designers can experiment with new cooling options, filters, and catalysts as a result of this freedom [28].
- Environmental Waste and Energy Reduction: Some of the general advantages of AM over conventional or subtractive manufacturing include material efficiency, resource efficiency, production flexibility, and part adaptability. In contrast to subtractive production, where, for example, a component is created from a full block of material by removing the excess base material. In the case of the AM, the attempt is to attach the support structure in such a way that the smallest possible production waste is pro-

duced through offcuts. The resource efficiencies refer to how simple AM machines are in comparison to traditional machinery, which requires auxiliary equipment, coolants, and tools, as well as emits and trash. AM uses fewer resources and so uses less energy than traditional machines since it requires less ancillary equipment. Smaller manufacturers can make parts closer to users because these ancillary devices and tools are not required for production, lowering transportation costs and associated emissions. AM enables part flexibility as a major aspect of waste reduction, in addition to the potential to minimise inventory and other wastes. Furthermore, production flexibility, or the capacity to move between different goods without having to invest a lot of time or money in setup, ensures a more efficient supply chain and cost-effective manufacturing batches to meet consumer demands [29–31].

AM in thermal management of electrical machines

For an electrical machine to function reliably and for a long time, thermal management is critical. This means that more efficient and better cooling capabilities are always needed. Conduction, convection, and radiation are the three processes that extract heat from an electrical machine [32]. Selecting an appropriate cooling system to optimise the convection effect is critical in order to limit the temperature of the machine's critical parameters. Thermal management on a machine is separated into two primary approaches and various sub-methods. Despite being more expensive, active cooling provides a substantially better cooling solution. The most dependable and least expensive method is passive cooling. Because of advancements in manufacturing technology, current solutions have grown more efficient. AM has various advantages for enhancing EM cooling capabilities, including decreasing weight, optimising forms and geometries, and eliminating assembly constraints. Figure 4 shows the thermal management methods for electrical machines [2].

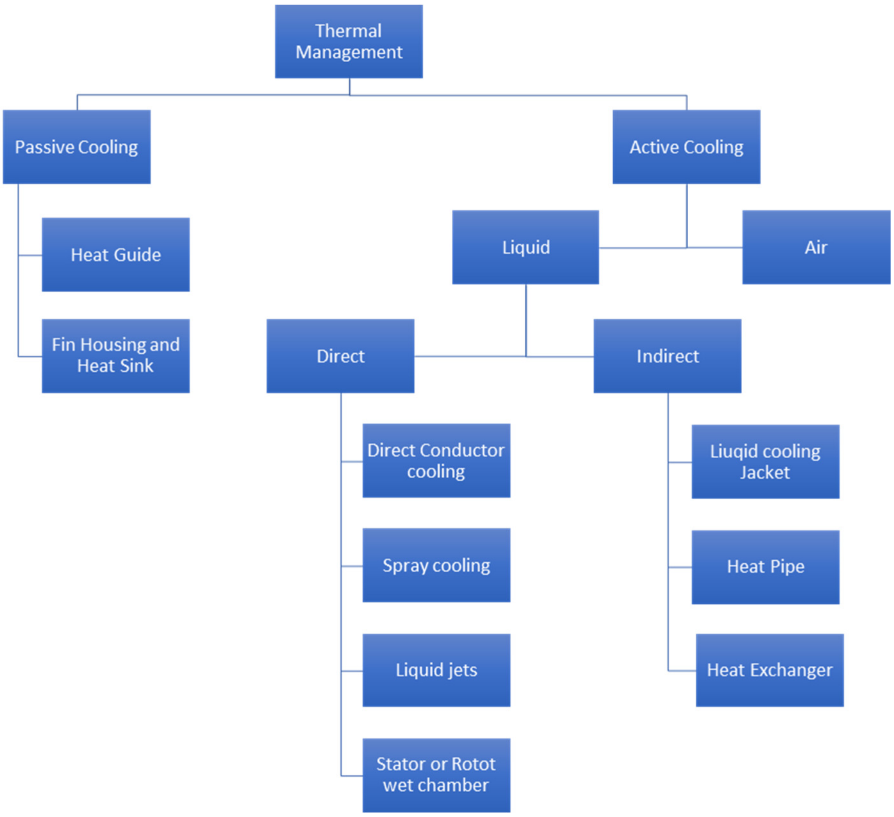

Figure 4. Thermal management methods for electrical machines.

AM-manufactured parts as a heat sink

In terms of thermal management, finned housings and air-cooled heat sinks are the favoured cooling methods for a wide range of electric and electronic devices. The air-cooled method is a simple, dependable, and cost-effective method of removing heat from electronic devices [33,34]. When the heat transfer coefficient or surface area in contact with air is raised, heat is taken from the system more efficiently [35]. The heat transfer coefficient of the active cooling finned structure and heat sink increases as the airflow rate increases. However, increasing the airflow rate may result in an increase in pressure drop, acoustic noise, and fan power consumption [36]. Due to the high acoustic sounds and power consumption, these two ways are less ideal for increasing the amount of heat extracted. The only viable option for boosting heat extraction is to use a larger heat sink. Several research investigations have employed the AM approach to overcome these constraints as an alternative to conventional manufacturing methods for fabricating passive and active heat sinks [37]. Wong et al. [38] presented a study that looked into the feasibility of employing AM to create active heat sinks. Three new heat sink configurations were designed and built (a staggering elliptical array, a lattice array, and a rectangular fin array with rounded edges). The researchers reported in their investigation that a heat sink with a lattice structure could not offer adequate heat transfer because the cooling air and heat sink structure could not interact with one another. Krishnan et al. [34] have developed a honeycomb concept to design heat sinks for air cooling in such a way that a minimum pressure loss is achieved. Their concept designs included using finned foam, honeycomb shapes, and Schwartz configurations to enhance the transfer of heat to forced convection streams. Moreover, the designs had a greater thermal performance when compared to conventional heat sinks. For applications with minimal pressure drops, the honeycomb design is more efficient thermally. Additionally, the fin foam design is better for applications with big pumping power demands and as a final observation, Schwartz configurations had better performance for applications that needed velocity and mass flow rates.

AM-manufactured parts as a Heat Exchanger

Heat exchangers are devices that transfer heat from one liquid to another. They may be found in everything from air conditioners to electric motors to rocket engines due to their extensive range of applications. Heat exchangers prevent overheating of equipment. When designing a part, a complex trade-off must be made between increasing the surface area of the part and limiting pressure drop. Several research papers [39–41] were conducted to investigate the implications of AM technology on the production of new heat exchangers. Microfeatures, crucial forms, and heat exchangers can be implemented with AM, reducing the number of parts. We can classify heat exchangers into two primary types utilising AM techniques: fluid-cooled heat exchangers and air-cooled heat exchangers and evaluate their thermal management. GE AM prototype heat exchangers were recently tested at temperatures of 900 °C, which is 200 °C higher than current state-of-the-art technology. The prototype, according to GE research, may be utilised in the energy sector to produce "cleaner, more efficient power generation in both existing and next-generation power plants and jet engine platforms" [42]. High torque densities are required in cars with electric motors, such as electric and hybrid vehicles. The stator slot and windings are where the majority of the losses occur in these devices. As a result, the thermal degradation of the stator slots and windings is a key stumbling block to creating and producing a high torque density motor [43]. Direct winding heat exchange (DWHX), as an advanced thermal management approach, can assist solve this problem by cooling the stator slot and windings by greatly reducing the thermal path between the windings and ambient air [44]. The liquid-cooled heat exchanger is an alternative to the oil-cooled motor that is designed to reduce the weight, cost, and complexity of the thermal management system [41]. A mixture of glycol and water is employed as a coolant in this technology. Lower pumping losses, better thermal characteristics, increased thermal performance, and better heat transfer for high-temperature applications are just a few of the benefits of this coolant [40].

AM-manufactured parts as a Liquid Cooling

The component design was greatly facilitated by AM in the form of direct design and manufacturing of complicated shapes. A key feature of AM is the high level of freedom in the design and processing of components with complex internal structures [45]. A cooling channel can be manufactured using AM, precisely according to the demands of the analysis, without the limitations of conventional machining techniques. As a result, cooling is even faster, resulting in higher efficiency and lower component costs. Several ongoing studies suggest that AM can replace traditional manufacturing techniques, particularly for components with a cooling channel, boosting quality and productivity. Based on the results of the literature analysis and case study, it was indicated that AM-aided cooling channels will become a popular production approach in the near future. Indirect liquid jacket cooling is a technology used on the stator's outer circumferential to provide primary thermal management for electrical devices or motors. Different publications depict a variety of cooling jackets produced using traditional methods. They have decreased manufacturing costs and complexity by streamlining liquid pathways. AM decreases production time, tooling costs, weight, and the total number of pieces for these cooling jackets [46–48] The TU fast racing team's latest housing design has a cooling-type pin structure to improve thermal management performance. They created a technique that can transfer more heat to the surface due to the increased surface area by using a 'pin' structure combined with 45° angled pins. Furthermore, the pin structure reduces flow separation and pressure drop, which promotes heat transfer from the coolant. Only metal additive manufacturing is capable of producing parts with this type of internal structure in a single piece. The enclosure was produced with AlSi10Mg using Laser Powder Bed Fusion (LPBF) on an EOS M-280 machine because of its low density, lightweight, good heat conductivity, and low cost. The electric motor was printed by AM without the use of any support structures due to the optimisation of the internal structure. Separating the inlet and outlet from the main body during the construction process also decreased the need for support structures on the part. Topologically optimised parts were made by racing team members utilising digital design tools to reduce weight by 0.6 kg. Through (computational fluid dynamics) CFD-optimised geometry, cooling performance and efficiency were increased by about 25%. The cooling mass flow rose by 27% after reducing pressure loss in the e-machine five times. With increased cooling mass flow, not only does the e-machine perform better in terms of cooling, but so do its other components, such as the radiator and inverter cooler [30,48,49].

Research Focus Area

An electric motor already in a research project is used as the basis for an exemplary improvement. The motor is located in an electric drive platform for NRMM. The motor is examined with regard to its water cooling and evaluated using the possibilities of additive manufacturing. The outer dimensions and shape of the motor remain fixed, as do the inner dimensions. Only the area of the water cooling can be changed within the framework of the experiment, with the advantages of additive manufacturing. These conditions are most likely to represent a real after-sales scenario in which a component is defective and needs to be replaced. Now additive manufacturing offers the possibility of manufacturing the component on location in parts more efficiently in quantities of one.

2.1. Problem Statement

The motor and battery are two of the most significant components of an electric drive train. Elements that have a significant impact on an electric motor's ability to use renewable energy for eco-friendly mobility include high power density, compact design, and high levels of efficiency. New generations of EVs have better batteries and motors that are cleaner and more fuel-efficient. One of the most important components in emerging vehicle architectures is EMs. These EMs produce significant amounts of heat during their operating and drive cycles. With an ambient temperature of 25 °C and a motor running at 7000 rpm, the motor temperature of an EV can reach more than 80 °C [50]. To offer maximum torque, high torque electric motors can be combined with high voltage batteries; however, they add weight to the system. Despite their tremendous efficiency, they also produce a significant amount of heat that must be evacuated. Lower temperatures may be acceptable, but greater temperatures may necessitate a reduction in power to maintain functionality. Even more crucial is the high voltage battery, which can only function within a specified temperature range and rapidly degrades due to heat expansion outside of this window. The heat generated by the motor during operation has a negative impact on its overall motor efficiency. The electric motor's torque and rotational speed are influenced by its temperature and internal losses, some of the losses include stator core losses and rotor core losses. Hence, it is very important that the temperature rise must be restricted to safe levels in order to maintain the enhanced motor's lifespan and for better driving efficiency. It is obvious that to prevent damage to the machine, the amount of heat generated must be effectively removed with appropriate cooling methods [51].

2.2. Approach to the Problem

An internal water jacket or cooling channel will be built in this study to efficiently dissipate the heat and keep the motor's temperature within the permitted range while utilising the least amount of energy and reducing overall motor losses.

By adding a water jacket or cooling channel to an electric motor, it is meant to boost heat convection rate, which thereby lowers the motor temperature in the traction zone, which used to be essential. Figure 5 illustrates the procedure.

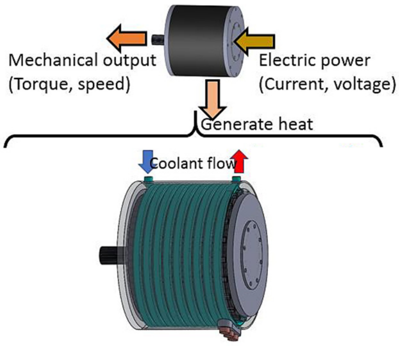

Figure 5. Approach to the problem.

A CFD model will first be constructed with the appropriate boundary conditions, in which water will flow from the water jacket and go around the motor casing using two different topology-optimised models. The output temperature, mass flow rate, and efficiency of these improved models will be examined using ANSYS CFD Fluent. Once we obtain the ANSYS CFD results for the topology-optimised water-cooling jackets. We will have a foundation for further developing this electric motor case utilising AM, where we may insert the lattice structure and water-cooling jackets. The mass flow rate, output temperature, fluid pressure, and efficiency of the AM motor casing may all be calculated here. The acquired results enable us to distinguish between the two topology-optimised motor casings.

2.3. Methodology

Water-cooling jackets are manufactured using AM methodology, enabling us to dissipate heat close to where it is generated. These cooling jackets are easy to produce and AM adds other advantages such as lightweight electric motor housings. Furthermore, they are able to handle complex geometries without the need for post-processing. Using parametric CAD modelling, several criteria for the design and optimisation of water jackets can be generated. To remove these losses from the motor and achieve better output conditions, the motor casing is topologically improved with a fluid cooling jacket. Once the optimised water jacket is finalised, the CAD model will be validated using the electric motor's thermal boundary conditions. The water–glycol fluid at about 1 bar pressure is pumped through these water-cooling jackets. ANSYS CFD post will be used to simulate the results and check their accuracy.

3. Result/Case Study

3.1. Electric Motor

The EM's function is to convert electrical energy into mechanical energy. Most EMs generate force in the form of torque applied to the motor's shaft by interacting between the magnetic field of the motor and the electric current in a wire winding.

For years, electrification approaches have been implemented in the automotive industry. Automotive manufacturers have already produced vehicles with hybrid or fully electric powertrains. The primary concern for automotive manufacturers in terms of electrification of vehicles or Non-Road Mobile Machinery (NRMM) is the overall heat generated by the motor, which has a significant impact on the overall performance of the EV or NRMM. For this research study, we chose a representative model of an automotive electric powertrain to aid in the development of modelling technology and simulation. The chosen automotive EM design, as shown in Figure 6, is modified to produce a better topology-optimised electric propulsion design.

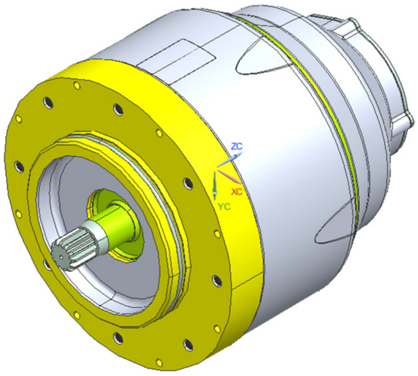

Figure 6. Electric Motor used in this study.

3.2. Water Jacket Topology

Water cooling has been widely used in the automotive industry for many years to cool EMs. Fan-cooled motors typically cannot provide all of the features that these solutions can. There are a variety of features available that can improve power efficiency, reduce noise levels, and enclose applications, among other things.

The majority of EMs transfer more than 90% of their electrical energy into mechanical energy, allowing them to run effectively. Additionally, the remaining 10% of a motor's electrical energy is wasted as heat. This waste heat can be efficiently dissipated by using a water-cooling system to protect the motor from overheating. New methods and manufacturing procedures were developed to investigate this motor type as technology has advanced, such as the topology model made using additive manufacturing with incorporated water-cooling channels. As shown in Figure 7, two different water-cooling jackets will be used in this study [52,53].

This enhanced design avoids the need to transmit heat through the metal housing to an external cooling sleeve, as heat losses can be dissipated through the water-cooling jackets from within the motor housing. Using this technique, we no longer need to employ an outer cooling sleeve. There are further advantages, such as lower thermal inertia and higher continuous output.

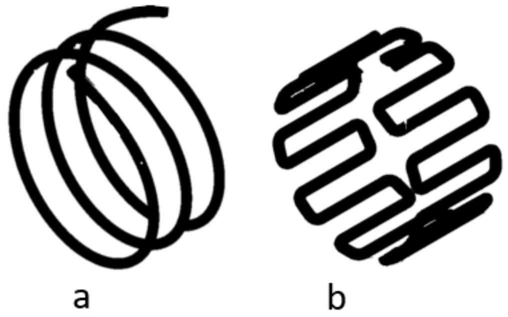

Figure 7. (**a**) Helical water jacket. (**b**) Axial water jacket.

3.3. Experiment Model 1

3.3.1. CAD Geometry

As shown in Figure 8a,b, the basic shape of EM geometry is a cylindrically structured housing with an inlet and outlet water-cooling connections. The internal radius of the EM geometry is 93.00 mm, while the outward external radius is 106.25 mm. The housing has a thickness of AlSi10Mg (Aluminum alloy) which is 13.25 mm and the overall length of the motor is 248.00 mm. These values are taken from the EM geometry which is mentioned in Figure 6.

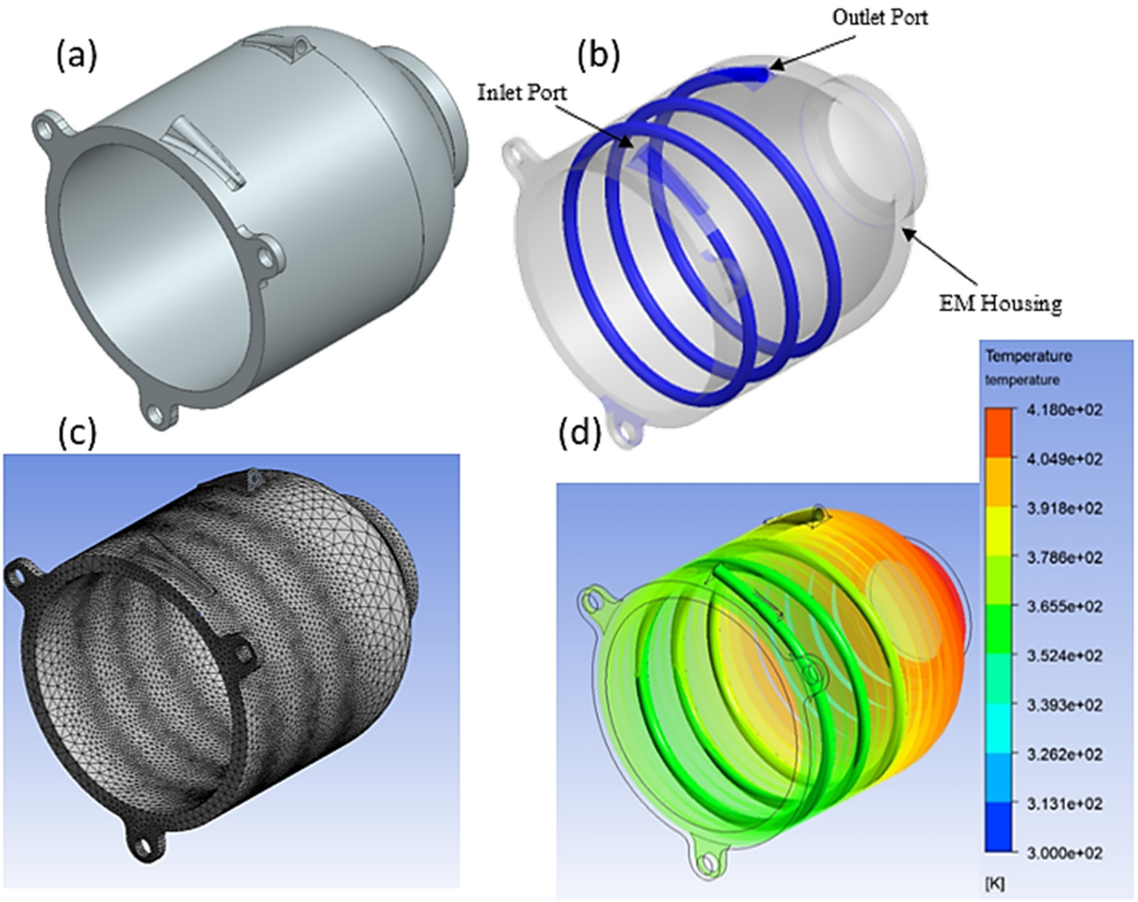

Figure 8. (**a**) CAD Geometry–EM housing. (**b**) CAD Geometry of helical water-cooling jacket. (**c**) Helical water jacket geometry meshing. (**d**) Motor housing temperature distribution with helical water jacket.

The primary factors influencing fluid flow are the geometry of the inlet and outlet flow channels, hence this study may benefit greatly from optimisation in these areas.

As seen in Figure 8b, the water–glycol fluid inlet and outlet are modelled in a helical-shaped geometry. The water-cooling pipe's combined surface area in contact with the housing is 59,232.00 mm^2. The helical water-cooling jacket has a diameter of 10.00 mm.

3.3.2. Thermal Simulation

An electric motor CFD model is prepared in order to study the motor's thermal and cooling characteristics. Simulation of the flow of water–glycol coolant, the heat conduction properties of the motor housing, and motor losses are carried out using this CFD model.

EM housing walls and helical water jacket walls were meshed using a quadratic element order computational mesh with an element size of 0.2 m, as shown in Figure 8c.

The model was solved for energy equations involving heat, temperature, pressure, and viscous turbulence. To simulate wall turbulence, a two equation-based k-epsilon turbulence model coupled with a standard wall treatment method was used. Material properties of AlSi10Mg (Aluminum alloy) for EM housing, such as density, thermal conductivity, and specific heat, were considered. A uniform thermal conductivity and motor loss source term are applied to the EM housing.

3.3.3. Boundary Conditions

The pump forces the water–glycol coolant mixture into the inlet port at 1 bar of inlet pressure. The mixture has a density of 1111.4 kg/m^3 and a specific heat Cp value of 2415 J/kg (kg-k). The EM housing is constructed of AlSi10Mg, which has a material density of 2780 kg/m^3 and a specific heat Cp value of 875 J/kg (kg-k). The electric motor's overall loss is 1.63 KW, which is added to the solid housing source term. The water–glycol coolant enters through the inlet port and exits through the outlet port, removing heat. The EM frame is exposed to ambient temperature via an external convective heat transfer coefficient.

3.3.4. CFD Results

This section shows the temperature distribution, mass flow rate, and total losses simulation results. Figure 8d depicts the temperature distribution in an EM housing with only a helical water jacket.

For helical-shaped water jacket cooling, the minimum and maximum temperatures recorded are 300°K at the inlet port and 418°K at the outlet.

Local heat generation, cooling fluid shortage in determining regions, or fluid local turbulence can all cause thermal differences or blank spots inside the water circuit. As shown in Figure 9a, the heat flow from the entire motor to the water is uniformly distributed across the frame surface.

It can be assumed that the cooling water jacket will be filled with water–glycol throughout the process, therefore there will be no shortage. Lower water velocity and pressure raise the temperature of the housing. Lower water velocity results in a lower heat transfer coefficient between the housing and the fluid.

Similarly, the fluid water–glycol mixture that entered the EM housing through the inlet port with an inlet pressure of 1.06×10^5 Pa exits with an outlet pressure of 1.01×10^5 Pa, as shown in Figure 9b. It is possible to calculate that there is a slight pressure drop during fluid flow. Water jacket design optimisations to reduce pressure drop are common to increase system efficiency and pumping power.

The simulation results also show that the mass flow rate at the inlet is 0.033 kg/s, which was calculated by putting the input boundary conditions in place. Shown in Table 1.

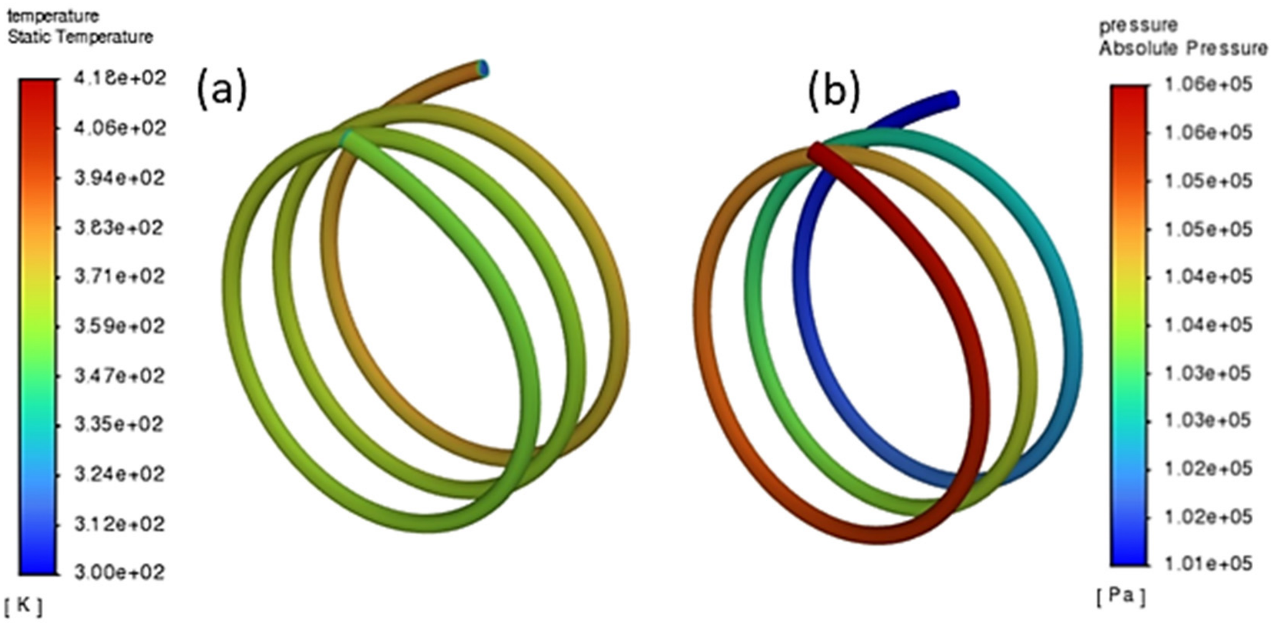

Figure 9. (**a**) Helical geometry temperature distribution. (**b**) Helical geometry pressure distribution.

Table 1. Mass flow rate from Helical water jacket.

Mass Flow Rate	[kg/s]
Inlet flow	0.033986126
outlet flow	−0.033986126

The EM's initial loss rate was 1.63 kW. The simulation results show that with the fluid flowing through the helical water jacket and housing, the motor total loss was reduced to around 0.4 kW. Shown in Table 2.

Table 2. Overall motor losses from Helical water jacket.

Total Heat Transfer Rate	[W]
Inlet	151.76473
Outlet	−1421.7511
Wall-7	−1669.5275
Wall-7 shadow	1669.5226
Motor loss source term	1673.1417
Net	403.15038

3.4. Experiment Model 2

3.4.1. CAD Geometry

Similarly, an experiment was conducted as mentioned on an axial water jacket. This EM, like the EM housing explained above, has a fundamental geometrical shape of a cylinder, as illustrated in Figure 10a. The EM geometry has an internal radius of 109.00 mm and an exterior radius of 123.00 mm. The thickness of the housing is 14.00 mm made up of AlSi10Mg, and the overall length of the motor is 255.00 mm with an axial water jacket diameter of 10.00 mm.

3.4.2. Thermal Simulation

On the axial water jacket housing, a quadratic element order mesh with an element size of 0.2 m was used. The energy equations were solved using two equation-based k-epsilon turbulence models in conjunction with a standard wall treatment method.

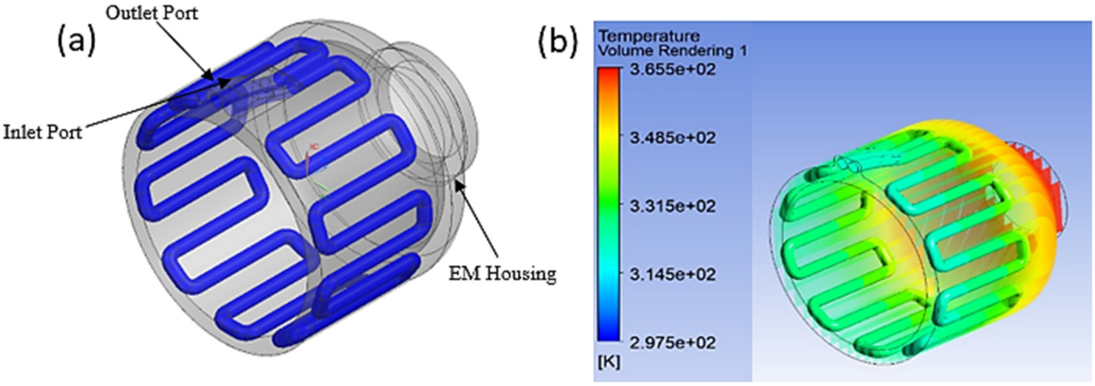

Figure 10. (**a**) CAD Geometry of axial water-cooling jacket. (**b**) Motor housing temperature distribution with axial water jacket.

3.4.3. Boundary Conditions

The same boundary conditions were used as shown above. The overall motor losses were calculated with the pump driving the water–glycol mixture at 1 bar through the input port.

3.4.4. CFD Results

This section displays the simulation results for temperature distribution, mass flow rate, and total losses. Figure 10b displays the temperature distribution in an EM housing with an axial water jacket.

The EM housing frame has a static temperature distribution. The minimum and maximum temperatures recorded for axial-shaped water jacket cooling are 298°K at the inlet port and 365°K at the outlet. Furthermore, the fluid water–glycol mixture entered the EM housing through the inlet port with an inlet pressure of 1.09×10^5 Pa and exited through the outlet port with a pressure drop of 1.01×10^5 Pa. Similar to the helical mass flow rate, the axial mass flow was also calculated. The results are as follows. Shown in Table 3.

Table 3. Mass flow rate from axial water jacket.

Mass Flow Rate	**[kg/s]**
Inlet flow	0.067355278
Outlet flow	−0.067355278

With the application of an axial water jacket in the EM housing, the motor losses were reduced to 0.4 kW when compared to EM losses with water cooling. Shown in Table 4.

Table 4. Overall motor losses from axial water jacket.

Total Heat Transfer Rate	**[W]**
Inlet	309.94173
Outlet	−1494.8248
Wall-7	−1618.6455
Wall-7 shadow	1618.643
Motor loss source term	1622.8028
Net	437.91719

4. Discussion

The introduction section explains the significance of aftermarket and spare components in the automotive industry. The automobile aftermarket is expected to rise by USD 21.5 billion by 2025 if only spare components are considered [1]. What would be quite critical to consider is whether this market situation will occur. Vehicle electrification will provide another significant boost to the aftermarket and spare parts businesses. The growth of additive manufacturing as an alternative manufacturing process has the potential to significantly improve the spare parts sectors. The key advantages include on-demand part creation, which reduces inventory costs, and the simplicity of having parts ready when needed. Another significant advantage of additive manufacturing in vehicle electrification is optimised designs, which allow for more weight reductions and improved thermal performance without sacrificing strength, quality, or safety [1,9,13].

This is followed by an overview of the spare parts sector and its problems with regard to the manufacture, supply and storage of parts. The spare part industry operates primarily on two principles: centralised and decentralised systems. Components in a centralised system are normally manufactured straight from the start of a product, stockpiled, and supplied centrally by the manufacturer, but in a decentralised system, a digital copy of the parts is maintained and physically produced on demand, reducing part stockpiling. In a decentralised system, the most significant factors are the CAD geometry and the availability of 3D-printing equipment. The digital spare part system may substantially assist industries, particularly the impact of the COVID-19 pandemic on the supply chain industry on a worldwide scale, forcing companies to explore different directions. AM or 3D printing are appealing primarily because they allow parts to be made in a formative manner. The researcher can ideally create new tools or parts with the support of DfAM standards. DfAM comprises four levels, each with its approach to product creation based on the demands and requirements. DfAM level four, for example, is characterised as a complete redesign of parts in terms of aesthetics, functional capabilities, and weight. DfAM has a wide range of potential uses in AM. Part consolidation is an innovative feature of AM that allows it to reduce part count while saving money and time. Another important component of AM is the capacity to create lattice structures, which reduce part weight while giving higher mechanical strength, which is limited in traditional building procedures. Because of the design freedom provided by AM, engineers can create structures with varying porosities, such as lattice structures. The AM technique, on the other hand, limits the use of material, lowering the amount of waste produced by traditional manufacturing. Overall, AM is vital in the future development of parts and can be a cost-effective way for businesses to flourish. The most promising aspect of AM in electrical equipment is its improved thermal management system. AM has the potential to select an appropriate cooling system to increase the convection effect by employing various AM methodologies such as passive and active cooling. Where direct or indirect cooling is applied, active cooling provides a substantially better cooling solution. Parts with integrated cooling jackets within the EM housing system can be produced utilising AM and direct cooling. In this process, the fluid circulates and removes heat from the housing, thereby preserving a specific necessary temperature and enhancing total system efficiency [21–23].

In this research, a direct internal water jacket was developed to investigate how cooling jackets efficiently disperse heat and keep the motor’s temperature within the permissible range while minimising total motor losses. Because these water-cooling jackets are made utilising additive manufacturing, we can dissipate heat close to where it is created. These cooling jackets are simple to manufacture and AM offers additional benefits such as lightweight electric motor housings by utilising a lattice structure. A CAD model was created in Siemens NX and then simulated in ANSYS CFD with the proper boundary conditions.

Fluid inlet pressure, motor losses, inlet temperature, and housing material were the boundary conditions. With the two direct water-cooling jacket topologies, the fluid will circulate around the EM housing. These upgraded models’ output temperature, mass flow rate, and efficiency were investigated. The results obtained allow us to distinguish between the two topology-optimised motor casings. A three-dimensional computational analysis of an EM housing with a cooling jacket drawn on the surface with water-glycol as a coolant under load conditions was performed. Firstly, the temperature field distribution was determined for various inlet flow rates and jacket configurations, as well as temperature dips between the inlet and output ports. In comparison to a helical water jacket, an axial water jacket assisted the housing in lowering the overall motor temperature by nearly 12%. For axial and helical cooling jackets, the output temperatures were 365°K and 418°K, respectively.

Secondly, increasing the number of flow passes around the EM housing lowers the maximum EM temperature while increasing the amount of power required to pump the water-glycol fluid. When compared to the helical and axial water jackets, there is a pressure drop in the fluid flow. The results show that as the number of cooling passes increases, the pressure decreases. When compared to each other, the helical and axial water jackets observed pressure drops of 0.4×10^5 Pa and 0.8×10^5 Pa, respectively, with a 50% decline. Finally, with initial motor losses of roughly 1.63 kW, it was discovered that putting a water-cooling jacket around the EM housing allows for a reduction in temperature as well as overall EM losses. The helical and axial water jacket motor losses were both seen to be 0.4 kW. The improved EM housing resulted in a 75% reduction in motor loss with a better heat transfer rate. Based on this research, it is possible to incorporate the water-cooling jacket so that the EM housing temperature is reduced while maintaining mechanical characteristics by utilising the design freedom provided by AM. In summary, the water-cooling jackets manufactured by AM can reduce energy consumption and increase efficiency due to their efficient design and close contour positioning. There is still space for improvement measures and critical considerations regarding the design. The water jacket could be further optimised and improved, for example, by introducing a structure into the channel or by optimising the design as shown by Stuve et al. [30]. In a further step, the simulation results could be verified by a real test to prove the functionality of the simulation.

The authors have posed a research question for this study.

“Can additive manufacturing with metal components contribute to more efficient mobility in the form of energy efficiency and environmental friendliness through spare and performance parts?”

The research question can be answered with “yes”. At least to a large extent, additive manufacturing can contribute to more efficient mobility. The following scenarios were discussed. On the one hand, by saving long supply chains and manufacturing the components at a distant place of actual use and, on the other hand, by increasing the power density of the components through additive manufacturing.

These scenarios include the advantages of additive manufacturing in terms of the possibility of more efficient production of the components and the freedom of design through to the manufacturing method itself. Functionally integrated components with adapted performance and topologically optimised can save resources and energy during production and use.

5. Conclusions

The spare parts sector in the automotive environment offers great potential.

Spare parts and performance parts will continue to be in demand and become increasingly important in the future. The components are becoming more and more efficient and adapted to the application. Additive manufacturing offers great potential for increasing performance density and resource-efficient production. This article uses a simulation of an electric motor for the NRMM sector as an example to illustrate this.

Potential for Further Research

Since the preceding research provides insight into how topology-optimised EM with a water-cooling jacket might improve efficiency and heat transfer rate, we may now investigate how future research work can be advanced using a combination of topology optimisation and lattice structure.

Lattice buildings can be crafted in a variety of methods, each with unique beauty and features. To generate 3D space-filling systems, new strategies for building cellular lattice structures with unit cells with extraordinarily high interconnected pore fractions have recently been devised. We can design reinforced and optimum structures with lattices by employing crosshatch sections made up of cells and nodes. Because of their small size, traditional production methods cannot match the requirements of lattices.

Lattice structures, such as the ones imaged in Figure 11, can support loads extremely efficiently when used as the cores of sandwich panels. Heat transfer across cross-flows can be achieved using the same structures. By conduction from a locally heated face sheet, heat is transported through the lattice structure and is dissipated through pore channels by a cross-flow.

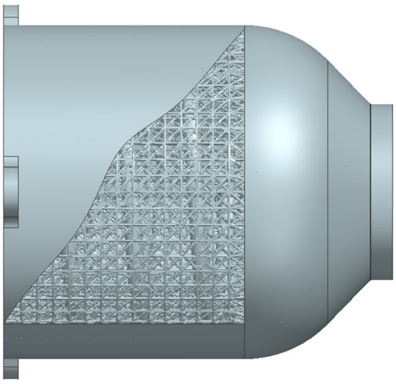

Figure 11. Helical geometry with lattice structures.

Due to their hollowed cross-sections, lattice structures dissipate heat more evenly and more quickly. By using AM, small features with large surface areas can be manufactured with higher efficiency for a wide range of heat exchanger applications [25,30,54].

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Abbreviations

Additive Manufacturing (AM); Electric Vehicle (EV); Direct current (DC); Compound annual growth rate (CAGR); Small- and medium-sized enterprises (SMEs); Design for Additive Manufacturing (DfAM); Laser Powder Bed Fusion (LPBF); Direct winding heat exchange (DWHX); Non-Road Mobile Machinery (NRMM); Electric motor (EM).

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