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An approach for reverse engineering and redesign of additive manufactured spare parts

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Abstract

The spare parts play a vital role in sustaining the operation and longevity of products and systems, but their unavailability can lead to prolonged downtime or expensive replacements. The integration of 3D scanning and Additive Manufacturing (AM) presents a promising path for spare part production. However, to utilise the full potential of AM, sometimes, redesign of the original part is needed. This paper investigates and proposes a new approach that integrates reverse engineering and redesign of an original part based on functional analysis to support the manufacturing of AM spare parts.

Keywords: reverse engineering, additive manufacturing, design for x (DfX)

1. Introduction

Spare or replacement parts play a vital role in maintaining the proper operation of a product or a system and can be used to extend their lifespan (Turrini and Meissner, 2019). Spare parts provide a cost-effective and efficient solution to address wear and damage of malfunctioning components, ensuring sustained functionality and performance of a product or a system over an extended period (Hu *et al.*, 2018). However, spare parts are not always easy to obtain, and their unavailability can lead to prolonged downtimes or even require costly replacement of the entire product or a system. The reasons for the unavailability of spare parts can be many, and some common ones are the lack of original parts on the market, supply disruptions that prolong the lead time for their procurement, or the loss of technical documentation needed for manufacturing spare parts. In such cases, one can use reverse engineering (RE) to design and manufacture the spare parts. The advent of 3D scanning technology in recent years has facilitated the RE processes, enabling easy and precise scanning of parts and obtaining their digital CAD models. Simultaneously, Additive Manufacturing (AM) has emerged as a versatile manufacturing process to produce physical parts directly from digital files without additional tooling and complex process planning. Hence, AM is becoming the go-to technology for manufacturing spare parts (Heinen and Hoberg, 2019; Knofius *et al.*, 2019). The synergy between 3D scanning and AM is becoming important in manufacturing spare parts as it enables fast and cost-effective design and manufacturing of various spare parts (Yao, 2005). Furthermore, it enables on-demand and on-the-site distributed manufacturing, which enables the production of a spare part only when needed, close to where it is needed, removing the need for extensive inventories and complex supply chains (Khajavi *et al.*, 2014). For example, Montero *et al.* (2018) used 3D scanning and AM to manufacture the spare valve cover of an electric diesel generator, while Kudrna *et al.* (2022) restored and upgraded the braking pedal of a historical motorcycle. Geng and Bidanda (2017) even talk about the concept of a "*3D Copier*", a machine that seamlessly integrates scanning and AM, enabling the replication of parts.

However, the integration of RE and AM for the production of spare parts is not without its challenges. The RE process based primarily on 3D scanning captures only the part's geometry without insight into its functionality. While such an approach enables an "as is it is" replication, when using AM to produce such spare parts, it is often not cost-effective because original parts designed for conventional manufacturing may possess excess material, increasing both time and cost in AM production. Furthermore, original products or parts are often designed with a specific manufacturing technology in mind and thus could contain certain manufacturing features in the design not relevant to part performance or operation (Pandilov *et al.*, 2018). At the same time, the layered nature of AM and the use of material different from the original can influence the performance of the part or cause a reduction in performance if the original design is replicated with AM without any modifications to address these issues. Therefore, the need for redesign often emerges to compensate for potential loss of performance and reduce AM's costs.

Simultaneously, AM offers unprecedented design freedom reflected in four complexities of AM: geometrical, hierarchical, material, and functional complexity (Gibson *et al.*, 2021). The utilisation of these complexities through the application of the Design for AM (DfAM) methods and tools could enable the redesign of the original part with the increase of performance and functionality while at the same time optimising the design to reduce production time and costs. But to enable the redesign with the aim of increasing part performance and functionality, capturing only geometry through RE is not sufficient, as one must understand parts functionality to conduct such redesign.

Hence, to address these challenges, we pose a question: How can we effectively combine RE and 3D scanning with DfAM methods and tools to redesign, and manufacture AM spare parts with the possibility of increased performance and functionality and form suitable for AM?

The structure of the paper is as follows: background and related work are presented in Section 2. Section 3 describes the proposed approach for RE and redesign of AM spare parts, while Section 4 depicts its application through a case study. The approach and the results of the case study are discussed in Section 5, while Section 6 concludes the paper.

2. Background

Reverse engineering (RE) is a process of creating a new product from an existing one and is a common industry practice. The RE can be used in many different contexts and for different purposes, from understanding design and decisions behind it, evaluation of competitors' solutions, to replication of existing designs or for analysis and archival purposes. Michaeli *et al.* (2017) divided the RE processes into two categories: processes for creating compatible components with a scanned object and processes for replicating parts. The later RE process incorporates scanning of the object and replication of that object by using an appropriate manufacturing technology and is often used for manufacturing spare parts. According to Buonamici *et al.* (2018), who conducted a review of RE methods and tools, the general RE framework is made of five steps: data capture and pre-processing; segmentation of the cloud point or mesh; classification of segments; surface modelling; and final CAD reconstruction. However, this framework only considers the RE of the product's or part's geometry, and the RE process based only on a geometric approach has a frozen design that does not provide design modifications (Durupt *et al.*, 2008). Hence, a knowledge-based approach that considers aspects of product functionality, form, physical principles, manufacturability, and assimilability (Otto and Wood, 1998) is needed to extract the original design intent to facilitate the redesign process. Urbanic (2015) stated that for redesign purposes, reconstruction of some type of functional model must be conducted to enable subsequent design changes during the redesign process. Such RE process can be seen in a RE canvas, a visual tool for supporting RE activities developed by Akerdad *et al.* (2021), where function structure is a key element of the RE process when one is trying to improve the existing design. Furthermore, Maier and Fadel (2009) emphasize that function structures are often used in RE and redesign scenarios when an existing product is analysed to understand how it works and how it could be improved.

Besides the role of function structure in the RE process, it is important to consider the impact of AM on RE. Akerdad *et al.* (2022) incorporated AM in education on RE to enable the manufacturing of redesigned products. The use of AM enabled students to experiment with the design and iterate it between process steps until a redesigned product satisfies the input requirements. Ali *et al*. (2013) combined AM with finite element analysis (FEA) in a RE process for redesign of a broken part. In their process, after digitalisation of a broken product and parametrization of the 3D CAD model, an FEA analysis is conducted to detect high-stress concentrations and modify the design accordingly, and AM is used to verify the new design. While in these examples AM is used to verify the RE redesign, Wang *et al*. (2021) uses AM to create an innovative design. They demonstrated the RE process where the redesign step is influenced by AM's manufacturing capabilities to create an innovative design with improved functionality, structure, or aesthetic.

When the application of RE and AM for manufacturing spare parts is considered, few approaches and proposals can be found in the literature. Dalpadulo *et al*. (2022) showed the application of RE and AM for manufacturing automotive spare parts. The main reason to apply the two is the unavailability of spare parts on the market, as these provide an on-demand production or small batch production that does not require dedicated tooling. In their review, they showed the process can be used to create exact replicas and to modify existing designs to improve the design or incorporate new features or aesthetic details. Montero *et al*. (2018) considered the use of RE and AM for the repair of deployed equipment to enable the manufacturing of spare parts close to the operational area of the equipment. They identified five stages of the RE design-manufacturing process which include scanning, repairing, parametrisation, optimisation, and verification. Later, they further developed their approach and proposed a process model of a deployed AM spare part production made of five phases: data-acquisition, design, proofing, manufacturing, and service phase (Montero *et al*., 2020).

As shown in the literature, RE has an important role in the manufacturing of spare parts, and AM introduces new possibilities in this application, enabling the redesign and improvement of spare parts' performance. However, the current approaches that integrate RE and AM are primarily focused only on RE of part geometry. At the same time, for RE to foster the redesign process, a deeper RE process is needed, which will include RE of form, functionality, and other aspects of the original design intent.

3. Methodology

To address the research question outlined in the introduction and with previous research in mind, we propose a new approach for RE and redesign of AM spare parts. The proposed approach builds on the existing body of knowledge in three main areas: geometrical RE, functional analysis and DfAM. Hence, the approach incorporates existing methods and tools to carry out specific steps with the commonly accepted workflow direction from the RE of the original product to the manufacturing of AM spare parts. The novelty of the proposed approach is the concurrent application of geometrical and functional analysis. Both are used to distinguish geometry that must be kept so that the part keeps its core functionality and compatibility with the system it is a part of, while the latter is used to define the function structure of a part needed for redesign purposes. Furthermore, the approach is focused on searching for new AM-based solutions to facilitate the adaptive redesign to utilise AM design possibilities, improve part functionality and performance, and ensure the compatibility of the new design with AM. The steps of the approach are defined as shown in Figure 1, with the workflow divided into four stages: RE, modelling and analysis, redesign, and, finally, AM manufacturing and quality control.

The process starts with selecting the part for which a redesigned spare part will be made. Not all parts will be suitable for this process. Reasons for it include the requirements for specific materials, tolerances, or specifications not achievable with AM, or it could be down to the limitations of the machines used for AM. In selecting the part, one should look for cases in which the use of AM and, more importantly, efforts put into the redesign for AM will bring some additional value, be it reduced lead time, improved performance and functionality, reduced costs of AM or some other value (Diegel *et al*., 2019). This step requires some experience in assessing the added value. Still, one could facilitate the selection process with the help of tools such as a model for evaluating AM feasibility (Ahtiluoto *et al*., 2019) where one can calculate the feasibility index, which depicts the sensibility of using AM to produce the given part. Once the part is selected, the redesign process starts with the RE stage, collecting all requirements regarding overall dimensions or operating conditions. These requirements are usually based on the position of the part within the overall system, working environment, etc. If there is no original documentation for the part, it is the engineer's task to estimate the requirements based on the system design or operational conditions and history. Here, new requirements can be defined using the same input information to improve the design and resolve potential operational issues. The redesigned spare part must satisfy all the listed requirements at the end of the redesign process.

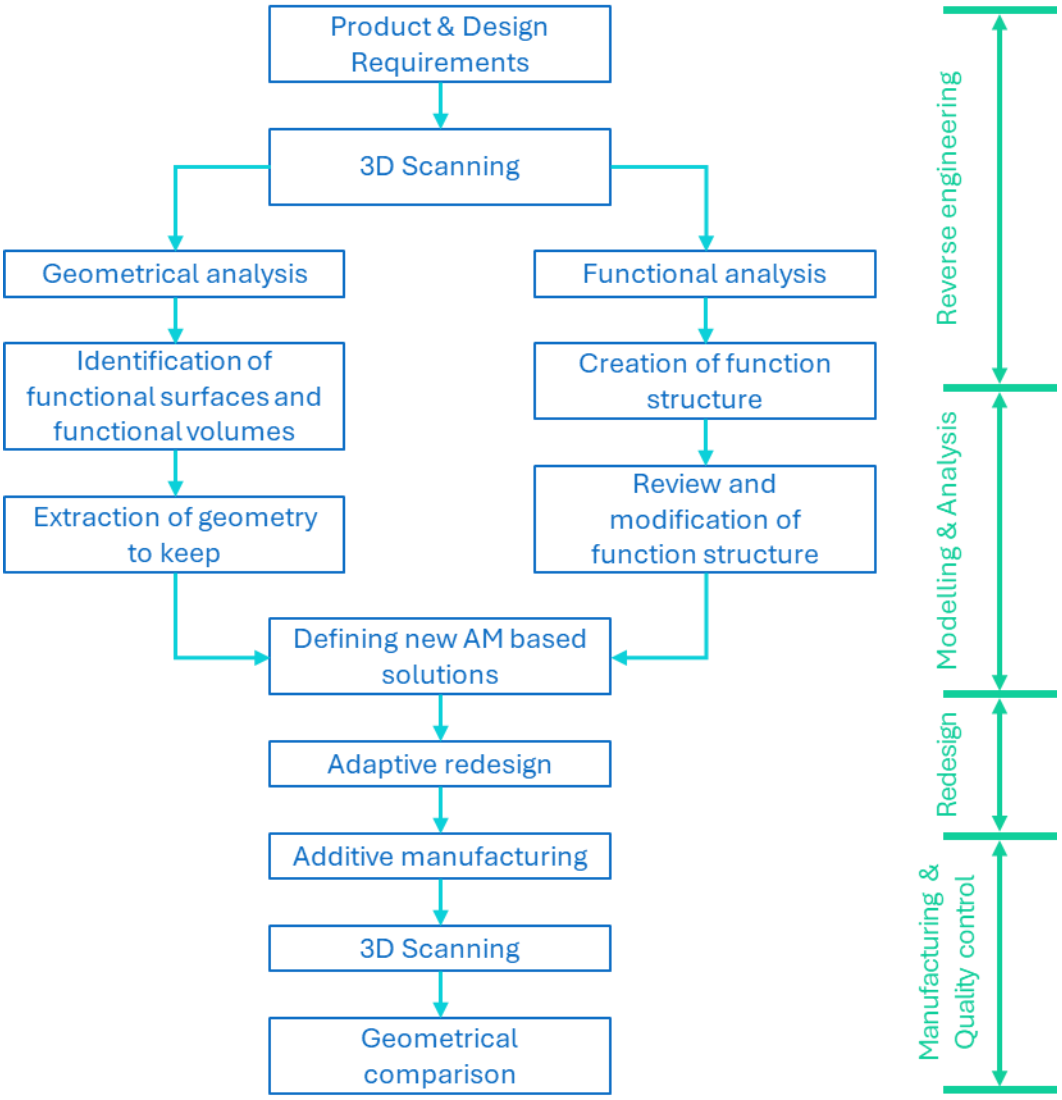

Figure 1. Outline of the approach for RE and redesign of AM spare parts

In the following step, the 3D scanning process is used to obtain the virtual 3D model of the part. The virtual model can then be used to check the geometry and features of the component, for virtual tests or to create prototypes, and as input for creating a new CAD model. The three main steps of every scanning process are obtaining the point cloud, aligning the captured scans, and polygonising to create a 3D model. Once the 3D model of a part is obtained, two analyses crucial for RE are performed - geometrical and functional analysis.

Geometrical analysis of the part is carried out to identify functional surfaces. As Yang *et al*. (2015) described, a functional surface is a surface that can fulfil a particular functional requirement and has specific geometric information, dimensions, and spatial location. Our focus are the functional surfaces of a part in direct contact with external parts or other components within an assembly. As these outer components are not included in the redesign process, those functional surfaces must remain intact, meaning all the above characteristics must remain after the redesign. The results of the geometrical analysis are used later in the modelling and analysis part of a workflow to define the design space that can be utilised in a redesign.

The second performed analysis in this stage is a functional analysis. The purpose of this step is to create a functional model of the part needed for redesign purposes. The analysis begins with defining the main function of the part, which is then divided into subfunctions through a process of functional decomposition to create a function structure. A function structure diagram is created by combining product subfunctions with material, energy, or signal flows into a meaningful representation of the system (Pahl *et al.*, 2007). It shows the transformation of each flow as the subfunctions perform action on them. While function structure can be created using the approaches of Pahl *et al*. (2007), or using functional basis vocabulary (Hirtz *et al.*, 2002), here it is recommended to create a functional model using the Function Class Method (Valjak and Bojčetić, 2023), as the functional model created with this method will be compatible with the mapping process later in the redesign process.

Once RE analysis is completed, the stage of modelling and analysis starts with the extraction of functional surfaces and modifications of the functional model. For each functional surface, a certain thickness is given to the surface, making it a functional volume (Ponche *et al*., 2012), which is extracted from a 3D CAD model. Thickness is defined based on experience and depends on the layer thickness of the AM process used. The functional volumes must remain intact, and the volume linking the functional volumes is intended to be a new design space for the redesign stage. As for the functional analysis, a function structure is reviewed and can be modified by adding new functions that the original product didn't have and that will be implemented in the redesigned product, potentially increasing part performance and functionality.

The created function structure, or multiple alternative function structures, are mapped using the mapping process (Valjak, 2022) to define new AM-based solutions for the part functions. The mapping process detects characteristic function chains or individual function blocks in function structure, and for each detected chain or block, it suggests one or more possible AM-based solutions in the form of AM design principles (Valjak *et al.*, 2022). Once the function structures are mapped, they are used in the adaptive redesign stage to create redesigned concepts of the part. Concepts are created by combining suggested AM design principles to solve the part subfunctions. This is followed by a design of a 3D model of a spare part that embodies the new AM-based solutions but keeps the functional volumes detected in geometrical analysis intact.

Lastly, once the CAD model of the redesigned part is created and compared to the established list of requirements, the manufacturing and quality control stage begins. This stage includes manufacturing of the part, the 3D scanning of a manufactured spare part, and a geometrical comparison between the original and spare parts. The redesigned spare part is manufactured using one of the AM processes and materials appropriate for the context. Although the AM processes can differ, they all include the preparation of the machine, the manufacturing of a spare part, and the subsequent processing of the spare part. After manufacturing, the spare part is scanned to make a geometric comparison. Comparison intends to analyse dimensional deviations of spare part from the original in the region of identified functional volumes and to confirm whether the new spare part meets the geometric accuracy. Furthermore, additional evaluation could be carried out to test mechanical performance such as strength, surface roughness, etc. If necessary, additional post-processing could be conducted to meet the listed requirements.

4. Case study

The proposed approach was applied to the case study as a form of initial verification (Teegavarapu *et al.*, 2008). The selected case study was a spur gear on which a proposed approach was applied (Rešetar, 2022). Spur gear is a common machine element found in many products and systems, and due to its simplicity, it is a good example to depict the proposed approach. The process started with the creation of a requirement list. There was no original technical documentation for the selected gear (Figure 2); hence, the requirements were established based on the designer's experience. The initial requirements were vertical position in the assembly and low rotation speeds. Due to the operational condition of the gear, an additional requirement was an improvement of passive cooling, while a lightweight design was added to reduce AM costs. The establishment of the requirements list was followed by 3D scanning of the gear to obtain its geometry. The 3D scanning was carried out on the GOM ATOS 5 device, and considering the size of a gear (70 mm in diameter and 10 mm thickness), a smaller measurement area (320 x 240 mm) was chosen. The obtained point cloud was processed using the GOM Software 2021, and the 3D model of the gear was created from which functional volumes of the gear were extracted (Figure 2).

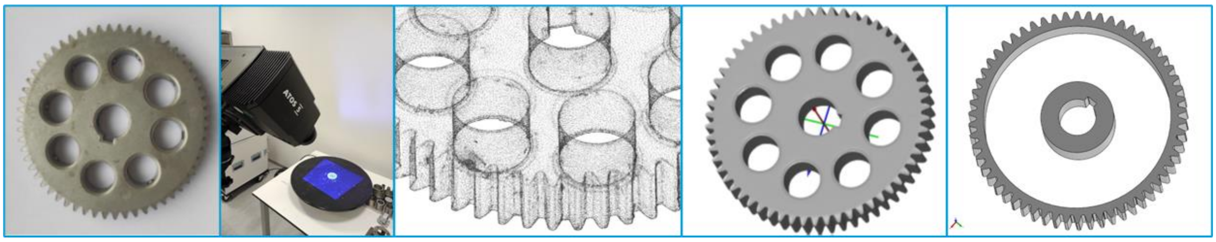

Figure 2. Original part; Scanning process; Point cloud; Obtained 3D model; Extracted functional volumes

Furthermore, a basic function structure of the spur gear (Figure 3) was created using the Function Class Method (Valjak and Bojčetić, 2023). The main functions are positioning and securing the shaft and the second gear required to transfer mechanical energy from the shaft through the gear onto the second gear. The function structure was reviewed, and multiple alternative function structures were created with the addition of a cooling function to dissipate the thermal energy caused by friction during the transmission of mechanical energy between gears, with different flow of medium used for cooling (gas or liquid). One variation is shown in Figure 4 as a mapped function structure that was mapped using the mapping methodology (Valjak, 2022) depicting the combination of design principles used for final redesign. The mapping process suggested possible partial solutions for function chains or individual function blocks in the form of design principles (Valjak *et al.*, 2022). No new AM-based solutions were considered for functions that describe the import and export of mechanical energy due to prior identified requirements and functional surfaces that cannot be modified. On the other hand, multiple AM-based solutions, such as topological optimisation, lattice structures, and void structures, were suggested for the function of guiding mechanical energy. Similarly, for functions regarding cooling, solutions based on complex internal channels feasible with AM were suggested.

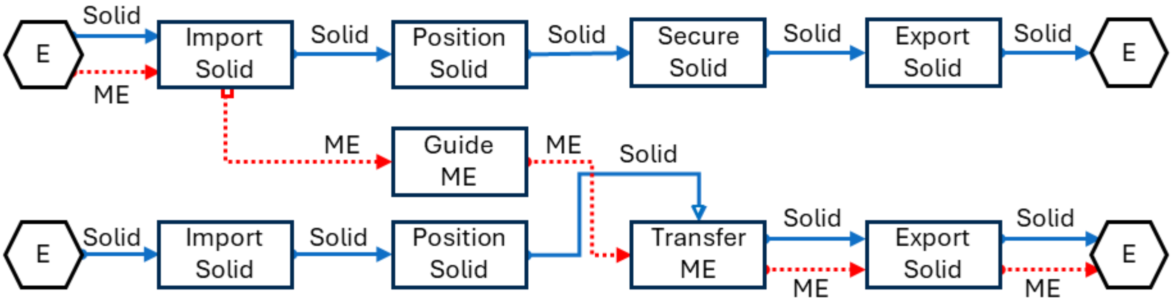

Figure 3. Functional volumes of the scanned spur gear; Function structure of the gear

By combining suggested AM solutions, multiple concepts of redesigned gear were created (Figure 5). One concept was selected, and the adaptive redesign was performed. The 3D model of a gear was redesigned to include new geometry and features. New features added to the gear model were a void structure to guide mechanical energy and reduce mass, vanes that catch the fluid and deliver it to the channels, and internal cooling channels. The idea behind cooling is that the gear is emersed into the liquid up to a quarter of its height, which enables vanes to grab the liquid and bring it to the channels. The channels have a larger diameter at the entrance and then branch into three smaller channels at the exit. Due to the rotation, the centrifugal force pushes the liquid through the channels. Internal channels like this can only be produced by AM, which clearly shows one of the advantages over conventional technologies. Furthermore, as the channel's exit is located on the teeth of the gear, the liquid that exits the channels lubricates the gear as additional functionality.

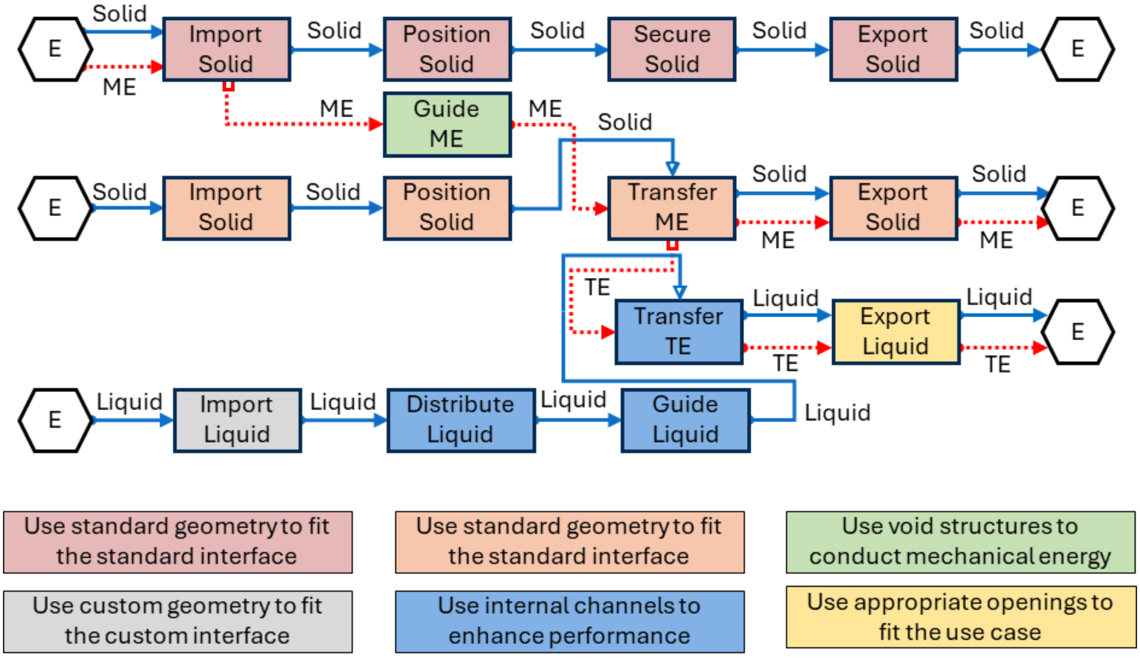

Figure 4. Mapped function structure and suggested design principles

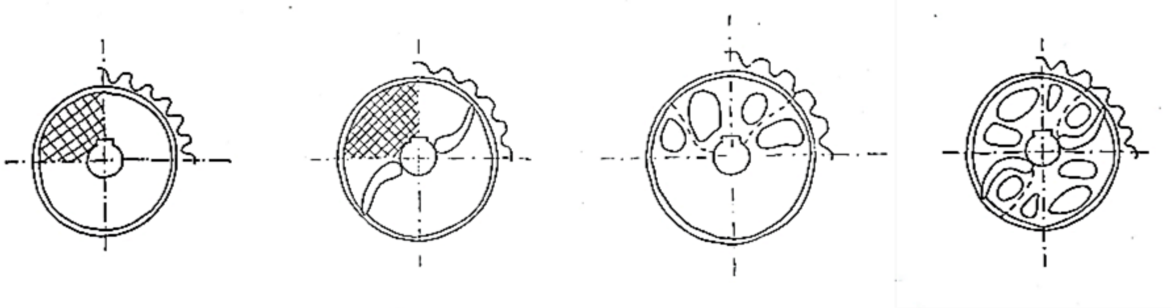

Figure 5. Concepts of the redesigned gear

Once the CAD model of the redesigned gear was completed, spare gear was manufactured using the EOS M 290 AM machine, based on the DMLS technique for metal AM, in stainless steel 316L (Figure 6). Afterwards, it was scanned using the same process as the original gear. The scans were compared to carry out a geometric comparison. Deviations were obtained by overlaying 3D scanned models in GOM Software 2021, as shown in Figure 6. The comparison showed no significant dimensional deviations in the region of functional volumes, i.e., the shaft hole and the gear teeth. Hence, the requirements posed in geometric analysis were satisfied. The final spare part is adapted to AM and incorporates some new solutions to improve its functionality and performance while satisfying the original requirements.

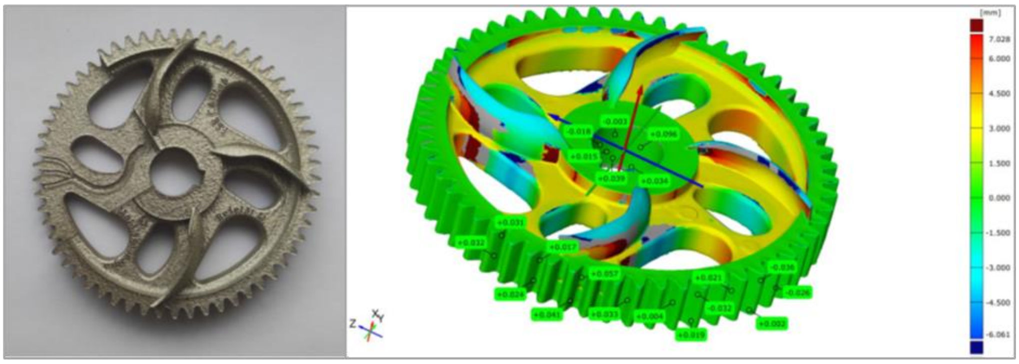

Figure 6. Manufactured redesigned gear; Geometrical comparison of scans

5. Discussion

Integrating RE, which includes both 3D scanning (geometrical RE) and functional analysis, with the DfAM approach and AM presents several benefits for manufacturing spare parts. First and foremost, 3D scanning and AM enable rapid, on-demand, and cost-effective manufacturing of spare parts. However, when the focus is solely on the geometry based RE process and replication of the original geometry as it is, it does not utilise the design freedom offered by AM; hence, a redesign process is needed. The proposed approach considers a knowledge-based approach to RE through functional analysis and creation of function structures for the reversed engineered part. This, in turn, facilitates the adaptive redesign process and enables the utilisation of DfAM methods and tools to achieve the redesign. The redesign's goal is to utilise design possibilities offered by AM to increase product performance and functionality, while optimising the design for new manufacturing technologies. This is achieved by incorporating function mapping, which suggests possible AM-based solutions for the developed functional structure and facilitates the utilisation of the aforementioned AM possibilities.

The presented case study illustrates the application of the proposed approach for manufacturing spare spur gear. The case study demonstrates the successful redesign and manufacture of the spare part with improvements in functionality and performance. Furthermore, it also depicts the suitability of creating a new design for the AM process, as it removes excess material in the original part designed for subtractive manufacturing and incorporates a form that reduces the need for support structures and minimises the required post-processing.

The proposed approach outlines the redesign process of spare parts on a high level, and it intends to guide a designer in using the RE, 3D scanning, and DfAM methods and tools to create a new part design while conforming to the initial requirements. The need for a careful selection of parts suitable for the proposed process is crucial. Certain requirements, such as specific material properties, tolerances, or specifications not achievable with AM, may render some parts unsuitable for this approach. Here lies the first limitation of the proposed approach, as it does not provide any support for selecting the suitable part for the redesign process. Not every part can be easily reverse-engineered or manufactured using AM, especially parts whose operational features and performances depend on the original manufacturing technology. Hence, this approach does not apply to every use case; it is intended for applications where the original design can be altered, and the use of AM and redesigns for AM can bring some new value to the product. Some examples of potential use could be manifolds that are usually bulky and with excess material, with perpendicularly drilled holes for guiding fluids. Redesign for AM could reduce the overall mass and optimise the trajectory of the internal holes (e.g. Diegel *et al*., 2019). Similarly, different brackets could benefit from a redesign for AM as incorporating topologically optimised structures could greatly reduce the overall mass and improve performance (e.g. Gibson *et al*., 2021).

The limitation of the approach is the lack of support for defining the initial set of requirements, and in current form is solely dependent on the expertise and experience of the designer. Similarly, the iterative nature of the redesign approach requires the designer's familiarity with RE, functional modelling, and DfAM to navigate the complexities of function structure mapping and adaptive redesign effectively.

Finally, in the presented approach, only deviations in the dimension were analysed during the geometrical comparison of the AM spare part. However, to ensure the operational readiness of the part, additional analysis, such as analysis of tolerances and surface roughness, should also be checked. If necessary, the part should be post-processed until it meets the required specifications. Future research could be focused on investigation of quality control and post-processing to provide greater level of applicability in practice.

6. Conclusion

In conclusion, the integration of reverse engineering, 3D scanning, and Design for Additive Manufacturing presents a promising approach to address the challenges of additive manufactured spare parts. The proposed approach outlines the high-level process for analysing and redesigning a part to ensure its manufacturability with AM, enable the utilisation of AM possibilities, and, through utilising AM possibilities, increase the functionality and performance of the spare part. The novelty of the approach is the concurrent application of geometrical and functional analysis needed as input for the redesign stage. The approach incorporates existing methods and tools for RE, functional modelling and redesigns from the literature. Furthermore, it requires the designer's expertise in some steps of the workflow, such as selecting suitable parts for the redesign or defining initial requirements.

Nevertheless, the approach provides a systematic workflow that guides the designer through the steps of 3D scanning, functional modelling, mapping, and redesign, as well as a structured set of steps for designing AM spare parts. The presented case study, focusing on redesigning a spur gear, serves as proof of concept for the proposed approach. However, future research must focus on resolving the limitations of the approach outlined in the discussion and validate the approach's usability in a broader context.

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