An approach to Reverse Engineering Methodology for Part Reconstruction with Additive Manufacturing

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Abstract: In diverse sectors such as aerospace, transport or energy, equipment is several decades old. Due to their extended lifespan, technical and manufacturing documentation might be inaccessible or inexistent. Manufacturing process problems, wear occurring during a part life cycle, or even the unavailability of digital data (redesign of obsolete parts produced in pre-digital era, legal restriction, or trade secrecy) are some examples to outline the lack of reliable 3D data for manufacturing purposes. The manufacturing and subsequent replacement of these components can turn into a significant problem. Lack of knowledge about system’s functioning, unknown operating conditions and limited technical information hamper the design development and manufacturing of these components. Classical Reverse Engineering (RE) approaches are commonly used to facilitate the understanding of a system’s functioning and ease the design recovery to create a more accurate and suitable model for engineered components. Combining these approaches with modern digitalisation technologies and new customized fabrication techniques, such additive manufacturing, can help to reconstruct obsolete, old or legacy components lacking manufacturing data. This paper contributes with a structured method aimed to design for additive manufacturing.

Keywords: Additive Manufacturing, Reverse Engineering, Product Life Cycle, Environmental, Design for Manufacturing.

1. Introduction

Manufacturing technologies are continuously improving over time, increasing the productivity and efficiency of manufacturing processes and allowing the production of complex designs in a cost-efficient way. The manufacturing of products is done at different scales ranging from humble domestic production of kitchen tools to the manufacturing of huge machines including ships, airplanes, and industrial machinery.

The word manufacturing technology is mainly used for the latter range of the spectrum of manufacturing and refers to the commercial industrial production of goods for sale and consumption with the help of gadgets and advanced machine tools. In addition, a component can be produced via a wide range of manufacturing technologies. Each technology possesses its own associated strengths and weaknesses [1].

Parts manufacturing technologies can be categorized into different categories, for example, giving primary shape, forming, material removing, joining, adding layers or material properties modifying.
The selection of the manufacturing technology to produce a specific component is not trivial and depends on several factors such as process-material compatibility, shape complexity, dimensional accuracy, superficial finishing, or production volume.

From the point of view of product design, when redesigning an obsolete part, in some cases, CAD models of mechanical components are not available, do not exist, or do not match the current geometry of the physical model. Issues related to the manufacturing process, such as the wear occurring during a life cycle of the part or even the unavailability of digital data (redesign of obsolete parts produced in pre-digital era, legal restriction, or trade secrecy) could explain the absence of accurate 3D data [2]. To counteract the lack of 3D data, Reverse Engineering (RE) approaches have been widely used in the last decades. Thanks to the rise of additive manufacturing technologies, complex shapes and components can be produced at low cost even in small lots, amplifying the benefits of Reverse Engineering [3].

This paper aims at developing a methodology that overcomes the manufacturing of existing components lacking technical drawings or CAD models with Additive Manufacturing (AM) technologies. Its main contribution is to develop a methodology that combines Reverse Engineering procedures with Additive Manufacturing design rules in order to ease the manufacturing of components lacking 3D data via Laser-Powder Bed Fusion (L-PBF). All the main research has been done at Siemens Energy.

2. Creating New and Spare Parts.
The part design reconstruction of existing systems or their redesign as an improved component/spare part require several activities to be considered. First, the functional requirements and geometrical features are to be obtained and analysed, to then select an appropriate list of materials that meets the pre-established requirements and a predefined design model. The selection of primary and secondary manufacturing technologies and particular post-processing techniques is also to be accounted.

2.1. Reverse Engineering vs Geometric Reverse Engineering
Reverse Engineering (RE) theories and methods traced back to the 1980s. Reverse engineering is generally addressed in the literature from different perspectives. In mechanical design, reverse engineering can be defined as a method to understand how a product works and the process of duplicating an object to obtain a surrogate model or a clone to enhance its performance, and to capture and apply the embedded knowledge for the development of a new design. However, the expansion of advanced digitisation techniques and modern engineering software and tools has resulted in the development of a new trend, sub-called geometric reverse engineering that aims to reconstruct the geometry of a component through advanced computational models and algorithms performed onto a point cloud data collected from modern digitisation systems [4,5,6,7].

2.2. Geometry reconstruction through Reverse Engineering
Reverse Engineering is a discipline covering a multitude of activities and is defined in manifold ways. Broadly speaking, Reverse Engineering can be defined as a systematic process that extracts design information from an existing product. In recent years, RE is acknowledged however as the process of creating a geometric CAD model of an existing component from 3D data acquired by scanning techniques.

Reverse Engineering is applied in various fields such as automobile and industrial manufacturing, medical purposes, design engineering, marketing enhancement, in the electronic and software industry but also in sectors associated with product piracy or plagiarism [4], [5], [8].

The introduction of AM as the primary manufacturing process has previously been stated as a possibility to reduce lead time, offer competitive manufacturing cost for low-volume production and enhance the design of complex components [9]. It is, therefore, interesting to adapt RE strategies into the AM process chain. These three factors are introduced in the proposed methodology as three different design concepts: one-to-one copy, linked to lead time reduction; adaptation for AM, associated with manufacturing cost reduction and optimise, aiming to enhance part performance. The proposed design
Concepts are linked to the inherent benefits of the AM and their selection relies on manufacturing considerations and established requirements.

Contrary to the common engineering and manufacturing workflow (a part is firstly designed and then, manufactured), RE starts with an already produced component, and then clones or redesigns the part into a digital model that can be utilized to manufacture the component (figure 1). These basic steps can be defined as an initial general framework for geometric reconstruction.

![Generic process of reverse engineering](source: original development based on Šag et al. 2015)

2.3. Data acquisition technologies and reconstruction methods
The data acquisition process, also known as digitization, is considered as the starting point in the Geometric Reverse Engineering process. Digitisation is the process of collecting the data of component’s surfaces and converting the acquired information into a digital form. As digitisation is the first step on the RE process, the accuracy of the acquisition process has a major impact on the subsequent steps. Data acquisition technologies are classified in two groups: contact and non-contact.

The Computer aided reconstruction method to be employed using the acquired digitisation data for the creation of a digital model depends on the desired result (parametric or non-parametric model). Typically, the outcome is accomplished by using very heterogeneous methods, resulting in the lack of a standard framework to tackle the geometry reconstruction. A complete classification of CAD reconstruction strategies is really challenging. The number of specific features that could be adopted as discriminating factors hamper the classification of the reconstruction strategies.

2.4. Material and Manufacturing Process Selection
Material-Process selection is a key activity in the product development process. As stated by Zaman et al. a lot of work has been done on traditional domain but very little in the Additive Manufacturing area. The designers working in the AM industry have to not only concentrate on the types of constraints involved in procedures such as Computer Aided Design (CAD) and the digitalization of their ideas, assessing capabilities of AM machines, and processing of materials to gauge the impact on properties, but also cater for new challenges and requirements associated with metrology and quality control, lack of generic interdependency between materials and processes, limitation in material selection, longer design cycle than manufacturing cycle, surface finishing issues and post-processing requirements [11].

Moreover, it is essential to choose the right compromise of materials, manufacturing processes and associated machines in early stages of design considering the Design for Additive Manufacturing guidelines.

Metal additive manufacturing is reaching the industrialization stage. While established additive manufacturing technologies are, somehow, finding some difficulties against technology-inherent cost
boundaries, new additive production concepts are shaking up the market. Therefore, and from the engineering perspective, it is essential to distinguish which technology is suitable for a certain application to produce quality and reliable components.

The ASTM F42 terminology divides the additive manufacturing technologies based on how the material is solidified into the desired component (table 1). In this matter, depending on the field of application, different materials and AM techniques are used. Manifold AM technologies can be divided in seven categories. Polymers, engineering plastics, ceramics, metals, metallic oxides, and metallic alloys are the most common materials used in AM processes. [12,15].

| Process                          | Table 1. Categories of Additive Manufacturing processes and their used material [12-15]. |
|----------------------------------|--------------------------------------------------------------------------------------|
| Vat photopolymerization          | Resin (liquid, paste)                                                               |
| Material jetting                 | Photopolymer (liquid), wax (melted)                                                 |
| Binder jetting                   | Diverse materials (powders, powder blends or particulate materials)                 |
| Powder bed fusion                | Thermoplastic polymers (powder), metals (powder), ceramics (powder)                 |
| Material extrusion               | Thermoplastic polymers (filament, paste), ceramics (filament, paste)                |
| Direct energy deposition         | Metals (powder, wire)                                                               |
| Sheet lamination                 | Paper, metals, polymers, composites (sheet material)                                |

3. Methodology Overview
The proposed methodology used in this contribution has been structured in three stages.

- First, a review of the existing literature covering reverse engineering approaches and their application for the design recovery of mechanical components is performed.
- Second, a deep analysis of modern digitalization techniques, data processing activities, advanced CAD reconstruction techniques, Design for Additive Manufacturing (DfAM) approaches, and part and material-process selection methodologies are conducted to provide a structured framework for the development of the methodology.
- In third place, a case-study of a spare part is carried out to exemplify the benefits of implementing the proposed methodology.

As presented in the previous section, Reverse Engineering (RE) is a broad concept and can be related to several fields. In the field of mechanical design, it has evolved from a method to understand the functioning of a system and capture embedded knowledge to a more elaborated process based on the utilization of advanced computational models, modern digitising technologies and software. RE has become a standard practice to replicate or repair a worn component when original data or specifications are unavailable, do not exist, or do not match the current geometry of the physical model [16].

The development of new scanning techniques in combination with the improvements in the field of the Additive Manufacturing (AM) have shown its potential to overcome the production of components lacking reliable 3D data. Indeed, thanks to the rise of additive manufacturing technologies, complex shapes can be produced at low cost even in small lots, amplifying the benefits of RE. However, there is not a standard procedure to tackle the geometry reconstruction and manufacturing of components lacking 3D data using AM as primary manufacturing technology. This project represents a proposal in the field of advanced design and development by defining a methodology in which reverse engineering strategies are performed to reconstruct special parts with Laser-Powder Bed Fusion (L-PBF) technology. The general working environment of the reverse engineering process i.e. input/output, influencing constraints/factors in the process and available resources to accomplish the desired outcome are to be understood. Figure 2 illustrates the main framework of the proposed methodology and highlights the implicated items and factors along the process.
The present work aims to create a new methodology for RE process in order to help designers to understand challenges and possibilities during the overall procedure. Manufacturing and material selection process, design analysis and evaluation and manufacturing planning are major operations of the methodology. Implications and limitations in each step of the RE process are highlighted to facilitate the understanding and manufacturing of a component. The use of knowledge extraction and design recovery methods, modern digitising technologies and software along with the assessment and evaluation of customer criteria and part attributes are incorporated.

The REtoAM methodology uses an adapted version of the IDEF0 (Integrated CAM DEFinition Language) methodology to develop and illustrate the proposal. The IDEF0 method is used for functional or activity modelling of a wide variety of automated and non-automated systems for existing and non-existing systems. IDEF0 describes any process as a series of linked activities, each with inputs and outputs. External or internal factors control each activity, and each activity requires one or more mechanisms or resources. Two primary modelling components are used in IDEF0: Functions and Data and objects that inter-relate those functions (represented by arrows).

For this aim the following methodology is proposed. The methodology is composed of phases, stages and activities (figure 3). It illustrates the hierarchy, structure and naming of the process introduced in the methodology. Each phase contains different stages and every stage a set of activities. Each phase, its stages and activities are numbered accordingly at their different levels. The REtoAM methodology is divided into the six following phases:

- Research and Analysis (R&A)
- Data acquisition
- Design development
- Manufacturing process planning
- Part manufacturing
- Quality inspection

The objective of the REtoAM methodology is to enhance the component knowledge through the Research and Analysis phase, from now on introduced as R&A, and thus, characterize the part by accumulating all the technical data and instructions of how a product works by means of classical RE methods, customer input and system’s knowledge. Gathering this information provides the designer the means to make informed decisions as to whether the current component design is adequate, or how it might be modified to add value and/or address the present set of design and manufacturing constraints.
This might be challenging as it could require engineers in different disciplines to capture all the ideas related to the components and its features and their interrelationships within a given system. In addition, the selection of the most manufacturing technology for the component is assessed at this first phase, determining whether the component should be manufactured using AM or by means of other Manufacturing technologies and techniques.

![Figure 3. The hierarchy, structure, and naming of the process in the methodology.](image)

In each stage of a phase, several key activities are defined. For example, the Evaluation stage at the Research and Analysis phase is composed of key activities such as data and information processing, manufacturing pre-selection and screening of Additive Manufacturing materials and machines.

### 4. Case Study, Results and Discussion

The case-study was an impeller that belongs to an old industrial water impeller, being one of the main components of a sea water desalination plant. The case-study follows the proposed REtoAM methodology. In this contribution, Laser Powder Bed Fusion (L-PBF) is selected as manufacturing technology because at the phase of “Material and Manufacturing Process Selection”, the technology was identified as the most suitable technology to accomplish functional, lead time and low-volume production requirements.

Once the material (using GRANTA Edu Pack©) and machine are selected, a design concept is to be chosen. Three design concepts are suggested in the methodology: one-to-one copy, adaptation for Additive Manufacturing or optimization (Design for Additive Manufacturing). The selection of a design concept is not trivial as it requires expertise and know-how obtained in previous case-studies. As aforementioned, the one-to-one copy is advantageous whenever lead time is the most critical factor and there is no intention of improving the part’s performance. Customer, mechanical and functional requirements are transformed into the sub-called decision criteria (lead time, cost, performance). The decision criteria were defined as: 70% lead time, 10% performance and 20% manufacturing costs. Since lead time represents the most decisive factor in terms of customer requirements, the one-to-one copy is selected as design concept.

The data acquisition phase is concerned about the measurement of the component. ATOS GOM
scanner in combination with manual measurement (electronic digital callipers) have been selected, in accordance with experts’ guidelines, as measuring technologies.

![Figure 4. Schematic representation of a generic pump.](image)

The ATOS GOM scanner has been selected due to its high acquisition speed, its relatively low cost and considerable accuracy. The technology is widely used to measure free-form shapes by the industry.

![Figure 5. Case-study component (left) and point data cloud (right).](image)

Using the information obtained in the part analysis phase and the scan data as a template, the model reconstruction was performed. A series of activities are previously done such as cleaning noise and defects from scan data, repairing of defects and holes up to, identification of features not previously detected in the analysis, determination of nominal dimension, design and manufacturing specifications.

The Siemens NX application is used to perform the geometrical reconstruction of the part. The process to create the case-study geometry works as follows:

- Create external wireframe geometry to obtain external geometry.
- Reconstruct internal channels geometry creating functional surfaces with wireframes.
- Subtract internal channels to external geometry.
- Implement detail modelling modifications to meet design specifications.

After that, the manufacturing process plan is developed according to the design and manufacturing specifications, the final part is printed using an EOS M290 machine and subsequently post-processed.

5. Conclusions

Literature exposes an absence of a general method to use embedded knowledge and information through
classical reverse engineering approaches, digitisation technologies and advanced software to develop accurate 3D models adequate for Additive Manufacturing technologies. This contribution highlights and demonstrates the benefits of implementing the methodology into a real-case project. A mechanical component of an old industrial pump model has successfully been reconstructed with reverse engineering and manufactured via Laser-Powder Bed Fusion (L-PBF) technology. The work has introduced a new framework for the analysis and evaluation of mechanical components, aiming to assess the implementation of additive manufacturing as the primary manufacturing technology and the recreation or re-design of the component’s design depending on the several factors, such as acquired knowledge through component analysis, part manufacturing feasibility and customer requirements.

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