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Lifecycle design and management of additive manufacturing technologies

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Abstract

Additive manufacturing (AM) is being proposed as a revolutionary manufacturing technology, promising significant advantages both from a design and production perspective. One challenge is the disruptive nature of AM and its impact on all life cycle phases.

This paper reports from a demonstrator project highlighting digitalization and process implications. A demonstrator tool was developed able to collectively capture and visualize different life cycle implications of AM products. Market expectations, technology characteristics and life cycle constraints were met in the demonstrator tool. Each individual part collected its own traceable data set, from design over manufacturing up to postproduction services. Key aspects demonstrated were 1) the need to represent any manufacturing and life cycle constraint already in design, 2) the need to integrate unique identifiers that build a digital twin and 3) the need to automate links between life cycle engineering steps.

Keywords: Manufacturing system; Product Development; Lifecycle

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1. Introduction

The benefits offered by Additive Manufacturing (AM) technologies are attracting interest within the manufacturing industry. Among other benefits, AM allows to create complex internal geometries, improving both functionality and enabling new levels of topology optimization [1]. Furthermore, AM allows to create sophisticated features that improve aesthetics and can be customized to suit individual customer preferences [2]. These benefits make AM an interesting technology especially for through-life engineering service providers [3]. One example is by “Contracting for Availability” (CfA) within the UK defence industry. AM has the potential to delocalize manufacturing that can occur anywhere within a port, a support ship or an aircraft carrier. Moreover, having manufacturing capability on-board allows the manufacturer to rapidly recover the product structure during repair [4].

While AM opens up new dimensions of the design space for product development, it comes with new sets of constraints and requirements that have yet to be explored. Such constraints are very different than conventional “design for X” (DfX) guidelines adopted today by engineers, which take into account lifecycle aspects already in the design activity. For example, established manufacturing methods and their limitations and implications such as injection moulding or machining lose their relevance [5]. At the same time, the freedom of AM reduces the need for Design for Assembly (DfA) [2]. Furthermore, because AM also allows for new and innovative maintenance and remanufacturing solutions such as the repair of turbine blades [6], it is considered to bring a major change in design paradigms [7]. In safety-critical industries, such as aerospace, this change requires the certification by authorities.

These premises suggest the need for engineers to rethink their conceptual barriers, which are often tacit in many cases [8], when considering lifecycle aspects in the design of products for AM. These needs have to be translated into “Design for Additive Manufacturing” (DfAM) knowledge, tools, rules, processes, and methodologies [9]. In fact, insufficient understanding of DfAM is advocated to be one of the factors limiting the uptake of AM in industry.

This study explores the challenges related to lifecycle design and management of AM technologies. The major finding is related to the need for designers to easily access information about lessons learned during the lifecycle design of AM components. In this way, a new knowledge base can rapidly be built inside the organization. For this purpose, a product lifecycle data management system is proposed in cooperation with industry partners. A functional prototype [10], the *DINA Demonstrator*, was developed to illustrate and analyse the correlations between design choices, process parameters, product life and use for all relevant stakeholders.

2. Research Method

The results of this study come from the cross-analysis between literature and the empirical findings derived from a Swedish research project conducted in collaboration with industrial partners and research institutes. The study was organized around the following research questions:

RQ1: *How can the uncertainties and unknowns about expected product behaviour for AM in the design phase be reduced?*

RQ2: *How can the relevant stakeholders access the information they need to reduce those uncertainties?*

Literature was first reviewed with the objective to find recognized needs for the lifecycle design of AM products. Articles were retrieved from the SCOPUS database through searching for specific sets of keywords such as: *key(“lifecycle design*” OR “design for”) AND key(“additive manufacturing” OR “3d printing”).* This list of needs was further explored and refined by the interaction with industrial practitioners participating in the research project. The participants were industrial experts working in roles that relate to the management of AM technologies inside the organization, ranging from technology managers to design engineers and manufacturing specialists. The outcome of this phase was a condensed list of three needs to be addressed by methodological support. This was developed as a functional prototype [10]. The results were then presented to a consortium of stakeholders from industry and society, where feedback was gathered through interaction of the participants with the prototype. The development of the functional prototype was done following Action Research [11] and Design Thinking [10] approaches: repetitive versions of the prototype were presented to the practitioners in small groups under guidance. This prototype-based approach was chosen as it allows to collect feedback considering also the users’ emotional state, as well as their stated and latent needs [10]. The main rationale for this choice was driven by the difficulty of running interviews as data collection method to understand the research problem, given the relatively novel design practices for AM established within the participating organizations.

3. Literature analysis: needs for supporting the lifecycle design of AM products

The literature analysis highlighted a number of critical needs important to support the successful design of AM products. *Rapid optimization of AM process parameters* is one of the earliest and most emphasized needs addressed in research. For example, AM applications have attempted to optimize process-related variables such as deposition rate to achieve quality and short lead times [12]. Researchers and practitioners have realized, however, that although these types of optimizations are still important, they have been applied to designs conceived for conventional manufacturing methods [13]. A greater advantage could be achieved by changing the designs so that they will be optimal when manufactured adopting AM [14]. In the context of Additive Manufacturing, a *rapid development of design experience* for this manufacturing technology inside the organization is stressed as a critical need for the successful uptake of AM in series production [15]. Digital technologies are therefore seen as a key enabler to inform designers about preferred directions for AM optimized designs. For example, [16] and [17] looked at software-based applications to generate support-free structures to avoid the long and tedious post-processing of AM designs. However, the ‘optimal design’ for AM is not straightforward: design choices create often trade-offs among multiple attributes of the product’s lifecycle [18]. For example, Zhang and Bernard [19] focus on the consequences of multiple AM designs (differentiated in terms of shape and orientation) manufactured in batch (differentiated in terms of placing) regarding build time, cost and part quality. Trade-offs between orientation choices and product performances in operation have also been explored [19]. Hence, literature emphasizes the critical need to *easily access information about lifecycle implications* of AM designs since the early phases. Technologies such as lifecycle data management [20] and visualization techniques [21] have the potential to support decision during design for AM. Due to the novelty and hence lack of information about the lifecycle behaviour of AM products, such technologies need to be extended. Literature stresses the need for *effective collaborative information sharing* between the design department and other organizational functions within – and even outside – the organization. The empirical study focused on exploring more in depth this last need, in order to arrive at the definition of a design support to improve decision making during the lifecycle design of AM products.

4. Empirical study findings: the criticality of sharing AM knowledge during design

From the interviews and interactions throughout the development and presentation of the product lifecycle data management system prototype, the following main needs were identified and subsequently addressed in the demonstrator. The main needs identified are also summarized in Table 1:

- *Easy accessibility of the entire product knowledge:* this was seen by practitioners as a critical need especially when designing AM products for maintenance and repair. Furthermore, the ability to quickly adapt manufacturing parameters, as enabled by AM technology, according to feedback from later life cycle stages encourages to rethink the common design process. Instead of relying on generalised design guidelines, developers can access product behaviour and manufacturing process data and from there derive product specific design knowledge. This is especially valuable when the prototyping process is already included in the data collection. The availability of product development data, such as the design rationale or the product platform, for stakeholders downstream in the product life cycle was stressed as a critical factor to ease manufacturing or maintenance work and reduce the potential for errors in these fields.
- *Traceability of individual product information:* All participants stressed the need for product traceability. Especially in the age of mass customization, it is of importance to be able to identify each product individually. The possibilities for individualized maintenance through AM were mentioned multiple times by the industrial practitioners. In this context, the need for traceability increases importance.
- *Automation of information flow:* The need for automation of the information flow between life-cycle steps and engineering was the main point to present with the demonstrator, which is illustrated below.

Table 1 Needs for AM data management and how they were satisfied in the prototype

Need	Feature in demonstrator
Easy accessibility of the entire product knowledge already in design	Adaptive configurator and data feedback flow
Traceability of individual product information	QR codes, scanning through mobile/handheld devices
Automate links between life cycle engineering steps.	Central database with browser based access

For the study, a demonstrator, where each individual product creates its own data set about manufacturing, measurement and post processing steps, was created. This process flow and respectively created data sets are illustrated in Fig. 1. The darkest area shows the information gathered for each individual product, whereas the grey area holds the process steps and information of the product that is common to each member of the product family, such as the target geometry and requirements. The white area represents the product platform, where the data concerning all possible products is stored.

Over the product life cycle, production, use, wear and performance data are to be collected, whereas in this demonstrator only the manufacturing aspect is taken account of. Each individual product is also associated with the respective product family and platform data. Fig. 1 shows these steps and the respective data set that is collected. The steps use, maintenance and end of life are hashed since they are not part of this iteration of the demonstrator.

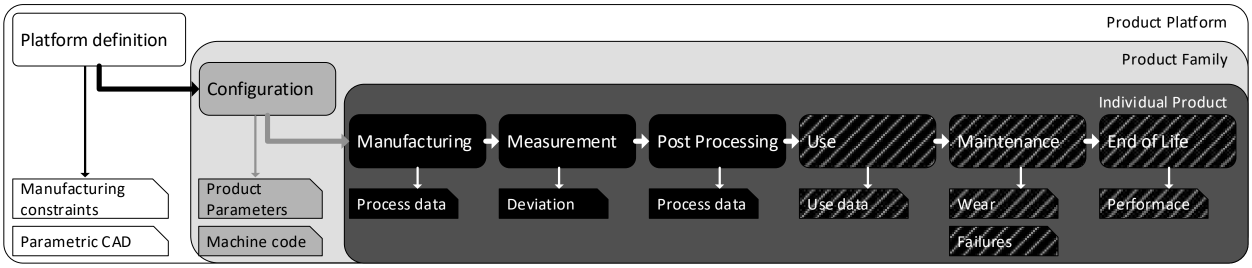


Fig. 1 Process- and data flow in the demonstrator. Hatched elements have not been realised due to time and resource constraints.

5. The DINA demonstrator: a product lifecycle data management prototype

To be able to adapt to the different requirements and abilities of the available AM methods, as well as different user requirements, a flexible product platform is created. As a sample product, a fictive jet-engine anchor point, as seen in Fig. 2, is designed. Its function is to provide a point for a crane-hook to move the engine in maintenance cases, and guides for cooling tubes and wiring. These functions were chosen to allow for a certain range of configurability. All features are fully parameterized.

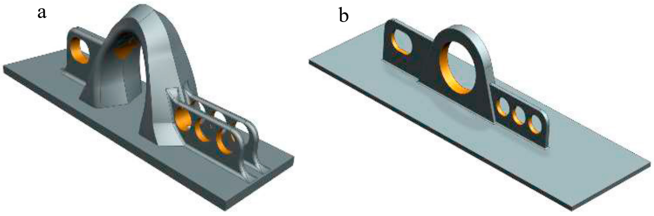
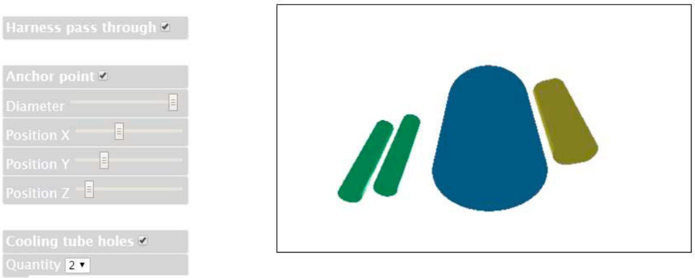


Fig. 2 Geometry of anchor point. (a) Laser-sinter model (b) metal deposition

The anchor point is realized as a small product platform, providing different geometries, optimized for the manufacturing requirements of the AM processes Metal Deposition and Laser Sintering. The geometries are realised in two parameterized CAD models, which can be adapted to the interfaces needed from the customer. A function-means model based on Enhanced Function-Means modelling [22] was created that contains the manufacturing constraints and user needs. Supported by the CAD models, the function model worked to instantiate the product platform. The CAD models incorporate all available interface configurations, therefore covering the geometric part of the design space, and fulfil the manufacturing constraints through the two geometries shown in Fig. 2.

Using the demonstrator tool, the sample product can be adapted via a web-interface integrated in the product data flow. The user is able to adjust position, size and number of openings. In addition, the user is able to choose the type of manufacturing process. A screenshot of the configuration interface is shown in Fig. 3.


Harness pass through ☑

Anchor point ☑
Diameter
Position X
Position Y
Position Z

Cooling tube holes ☑
Quantity 2 ▾

Fig. 3 Configuration interface with 3D illustration of interfaces

5.1. Implementation of the DINA demonstrator

The demonstrator tool aims to present how the lifecycle properties of AM products can be communicated, managed and shared during the design process. Table 1 summarized the main features that intend to satisfy the needs identified during the research project. The demonstrator is created as a product database, and collects different data sets for the purpose of illustrating product development and production data. Based on a configurable sample product, data for different steps of the production cycle is created. The demonstrator can be easily accessed via a web-interface, either via URL or directly via QR code as explained in chapter 5.2

By instantiating a configuration for an individual product of the product platform through the user, a CAD model of the geometry is created based on the above-mentioned parameterized model of the product family. With the

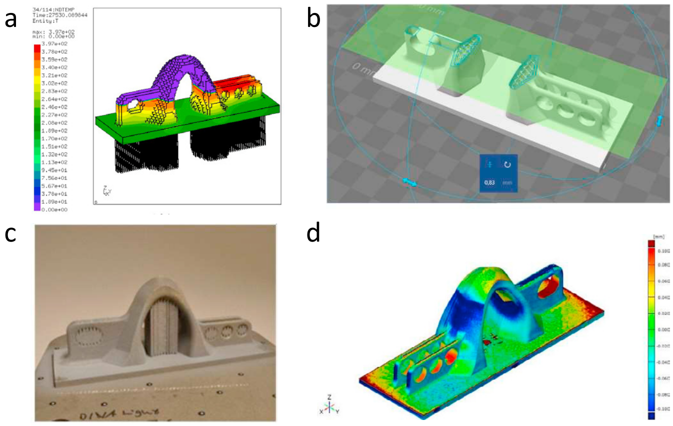


Fig. 4 Illustrations from the life-cycle data management tool: (a) Temperature distribution during AM, (b) slicing of CAD model, (c) un-machined part and (d) deviation of final 3D scan from original CAD model

Fig. 5 QR code for "partID 13", which is shown in Fig. 4. The code is functional and redirects to the actual demonstrator.

instantiation of the part, an individual dataset for this product family is created. After the initiation of the interface configuration, the manufacturing steps are shown, although different steps depending on the chosen manufacturing method metal deposition (MD) or powder-bed fusion (PB).

The "Performance" section shows the results of a structural FEM analysis. The "preparation" tab shows the actual geometry to be manufactured in the MD case, and a heat distribution simulation of the sinter process for the PB process, see Fig. 4 (a). Manufacturing shows the slicing of the part for the production process, see Fig. 4 (b). As soon as the part is manufactured, pictures of the actual part are added to the information set, as shown in Fig. 4 (c). In the next step, the deviation between original CAD model and a 3D scan of the product is shown in the PB case, where the MD case shows a 3D model of the scan in addition to that. The machining step shows a simulation of the machining paths that are required to reach the final shape, which is illustrated in the last step "final scan" together with another deviation between scan and original model, see Fig. 4 (d).

5.2. Support for Traceability: QR codes and scanning

To ensure the availability of the entire data set to each stakeholder who encounters the product, each product is equipped with a matrix barcode (QR code) as shown in Fig. 5. In the demonstrator, this was realized by QR codes printed on labels. However, to ensure a reliable tracking throughout the life cycle, laser etching of the bar code is recommended. Compared to labels, etched codes are permanently fused to the part.

QR codes were chosen since they can be easily read by a multitude of devices, can be applied to almost any surface and provide a high reliability in terms of readability even if parts of it are unreadable or the surface is bent. Furthermore, it requires a minimal invasion in the part to be tracked.

While it is of importance to access all information about a part at hand, parts have to be assessed and monitored remotely as well. Therefore, the demonstrator interface is equipped with a selection interface for all parts in circulation, sorted by configuration and type.

6. Discussion and Conclusions

The DINA demonstrator created in this project provides a way to collect and present information to each relevant stakeholder about the product creation and development process. From this information set, developers and engineers can derive guidelines for the design of AM products. This chapter collects the main feedback gathered from practitioners, researchers and stakeholders.

While it was enhanced that although the demonstrator was clear and easy to grasp, the large amounts of data that would be gathered over an actual product life cycle would have to be well presented. The centralistic data gathering approach eases the access, but makes it more difficult to sort and filter relevant product knowledge.

However, the ease of access to the entire data set of a product also raised questions of data security that will have to be addressed in future research.

Furthermore, the flimsiness of the identifiers on labels was stated several times, however retracted after being informed about the intended laser-etching solution, which would be able to survive all use- and manufacturing cases.

The main critique raised was that of feasibility, in the points of data collection, storage and representation.

Although each engineering and manufacturing process creates digital data that can be easily stored, a coordinated collection effort beyond existing product lifecycle management (PLM) tools would have to be done to create a data structure as shown in Fig. 1. It comes along with the problems of file versioning, different file formats and systems and required licenses to read and write the data. Although there are existing solutions to most aspects of these problems, an integrated solution is still challenging. Manufacturing data poses similar issues as engineering data. Although most machines produce detailed log- and process-files, there is usually no interface to collect them in an automated fashion. In addition, they are often stored in proprietary file formats, which again bring the issue of licencing and data interaction.

The storage of data is mainly a cost- or capacity problem, since a single set of production data is easily several gigabyte (GB) of data. Although memory is constantly getting cheaper, it is still costly especially when data security and backups are considered.

Data accessibility is a challenge of cognitive ergonomics, since many different data sets, which often contain several million data points will have to be made accessible in an easy and understandable fashion. Since one of the purposes of this product knowledge management tool are comparison tasks, the data will have to be formatted in similar formats and/or file types.

The demonstrator has effectively shown how it can be possible to collect and access product and production data in an additive manufacturing context. Relevant information from the first life-cycle stages is collected and made accessible in one single database. Although the demonstrator prototype is only functional as an illustration of potential product data and spans only the production phase of the life cycle, it already allows for the easy accessibility for all relevant product data, either directly via scanning the product itself or from a product overview. Each product has its individual data set it is connected to. Furthermore, the product can be adapted to stakeholder needs and required functions are matched with a respective geometry, matching the capabilities of the chosen manufacturing technology.

The demonstrator's potential is recognized by stakeholders from manufacturing, design and management. While there are still concerns about data safety and realisation, the approach is seen as a step towards the introduction of AM as a regular production method.

Collecting detailed product data of AM products over the entire life cycle, including usage, behaviour and maintenance, allows to establish trust in the method. The gathered data enables engineers to draw correlations between product behaviour, product design and process settings. Through the flexibility of AM, designers can react quickly with product changes once unexpected behaviour is detected. It can even be envisioned that design automation can benefit from the accessibility of such a vast data stock about product behaviour. Furthermore, the access to detailed product knowledge enables new levels of remanufacturing.

While this approach shares features such as unique identifiers and horizontal integration with the concept of Industry 4.0 [23], it follows a different goal. The approach mentioned here is not only focused in improving and speeding up product development and production processes, but to enhance the knowledge about additive manufacturing and ultimately establish DfAM guidelines.

6.1. Further work

Since the demonstrator lacks an actual connection to the manufacturing system, the creation of individual parts is done manually, as well as the creation of the part-individual dataset.

The data set would be continued from this point on with data about assembly, distribution to complete the manufacturing aspects, and furthermore with customer, use, manufacturing and end-of-life (EoL) datasets. These are, however, not realized in the pre-study that is covered by this article and are subject to further work.

The data that is collected in the demonstrator stretched over the entire manufacturing process of the mounting bracket and illustrated each step in it. Since it was only a demonstrator, the information was collected and stored manually, to give the impression of a continuous data flow. This limitation, as opposed to an actual automated data collection and storing mechanic, is due to the limited time and resources of the project.

In a next step, a new demonstrator based on the results from the initial prototype will be created. The basic functionality will be based on the demonstrator presented here, but covering more life cycle phases to allow the collection of use, maintenance and end-of-life data. Furthermore, the tool will be connected directly to the sources of production data such as manufacturing equipment or design software, allowing for the capture and reproduction of detailed product information. The demonstrator will be implemented in cooperation with Swedish small and medium enterprises and tested extensively. The further research will have to answer the questions about how to implement and maintain this method.

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