AALBORG UNIVERSITY

MASTER'S THESIS

Design for Additive Manufacturing - Internal and external integration in the Aerospace and Medical industries

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Synopsis:

An academic deductive research about internal and external integration for design for Additive Manufacturing in the Aerospace and Medical industries. This study seeks to identify key enablers in successful collaborations for design for AM projects.

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By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for all contents of the project.

ABSTRACT

Purpose – The goal of this study is to understand how different functions within the organization as well as external to the organization collaborated for design for Additive Manufacturing projects. The focus is to investigate the key enablers for such collaborations in the Aerospace and Medical industries.

Design/ methodology /approach – This study was conducted with a deductive research approach. A systematic literature review process on design for X, design for AM, and supply chain integration create the base of the theory that helped to develop a hypothesis for this project. The treatment of multiple Additive Manufacturing case studies by a CIMO logic analysis and the further cross-industry analysis were used together with characteristics identified in literature with the objective of answering the research questions.

Findings – The CIMO framework applied to the cases from Aerospace and Medical industries evidence a clear pattern of a much higher external collaboration between supplier and customer. The assessment of all cases offers the answer to the key enablers in successful collaborations for design for AM.

Research limitations/implications – The research faced limitations in terms of time and resources. Due to the unplanned event of the COVID-19 global pandemic, this study was limited in data collection. Furthermore, this thesis aimed to perform an integrated approach using both primary and secondary data, but due to the reason mentioned above, it was not possible to fill some data gaps by performing interviews with AM service providers.

Practical implications – Based on the literature and the CIMO analysis, this study presents some propositions to a better supply chain integration for design of AM in this kind of industry.

Originality/value – This viewpoint is based on an extended review of relevant literature and the CIMO analysis of successful Additive Manufacturing case studies. This study focusses on the Aerospace and Medical industries, fields where the research for integration for DfAM was scarce. This should be of value for both the suppliers and customers interested in understanding the key enablers for future collaborations.

Keywords – Design for AM, Integration, Enablers, Aerospace, Medical, Collaboration

Paper type – Master's Thesis

LIST OF ABBREVIATIONS

AM – Additive Manufacturing

CAD - Computer-aided Design

FDA - Food and Drug Administration

DfAM - Design for additive manufacturing

DfX – Design for excellence

DfNPD – Design for new product development

SC – Supply Chain

NPD – New Product Development

CIMO – Context, Intervention, Mechanisms, Outcomes

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1 INTRODUCTION

In the past two decades Additive manufacturing (AM) has undergone a major transformation, with the improvements of materials and technologies, experiencing an extraordinary market grow (Thompson et al. 2016). The basic principle of AM is that a model, initially generated using a three-dimensional Computer Aided Design (CAD) system, can be fabricated directly without the need for process planning (Radharamanan 2018). Offering the ability to build parts with geometric and material complexities that could not be produced by subtractive manufacturing processes. AM technology is already positioned at a maturity state, ready to be implemented, in the years from 2016 to 2020 (Shanler 2016).

The technology has been investigated thoroughly, and its applications have changed from being big and expensive, single dedicated machines to cheaper and small, multipurpose desktop printers. Also, more materials are introduced which makes the technology more applicable in more situations. AM processes have different batch sizes, production times, and cost drivers than traditional processes and require different approaches.

Additive manufacturing is also a target of several investigations because it provides different solutions to different user groups. It has caught the medical world's attention with the possibility of printing personalized medical devices in an effortless way (Di Prima et al. 2016). Also, it has gained the interest in the Aerospace field due to the capability of AM to handle aerospace components complex geometry (Thomas et al. 1996).

In the aerospace field, performance improvement or weight reducing are constrains with the same or even higher importance as production cost (Gibson 2017). In such highly regulated, high-performance industries like in aerospace, the weight reducing in existing designs or the boost of functionalities with new designs is seen as something quite advantageous.

According to Gibson (2017)[1], when using conventional manufacturing, performance can be compromised by the existing necessity of breaking the design into sub-components. The need for assemble may add mass and increase the risk of failure of the final

[1] Gibson, I. (2017). The changing face of additive manufacturing. Journal of Manufacturing Technology Management, 28(1), 10–17. https://doi.org/10.1108/JMTM-12-2016-0182

products. With the use of AM, technologies such as topology optimization and hollow-core structures can be used to eliminate these problems.

The medical industry benefits the ability to produce customizable products specifically designed to fit human anatomy. The focus has been on producing biomedical implants, customized casts, splits, prosthetics, and orthotics (Gibson 2017). Due to the profound effects that medical devices may have on patient health and well-being, agencies as the FDA [2] execute designated thorough laboratory examinations to additively manufactured devices in order to be validated (Di Prima et al. 2016).

The characteristics of different AM processes and materials demand distinct approaches to the design process. It is then important to make sure, whenever possible, products are specifically designed for AM. Design for Additive Manufacturing (DfAM) respects those imposed constraints, the entire part is redesigned to maximize the benefits of AM, and for how the part will be printed. Before starting the individual part design, engineers should analyse their product to see which value-adding strategies they should adopt. This will have an impact on the product structure and part configuration (Diegel, Nordin, and Motte 2019b). The lack of knowledge of DfAM can act as a barrier to unlock the full potential of additive manufacturing (Thompson et al. 2016).

This thesis aims to research in which way are the costumer and supplier involved in the Design for Additive Manufacturing and understand the motivations behind this participation. This thesis argues that the integration of design for additive manufacturing, particularly in the aerospace and medical industry, promotes a much higher external collaboration between supplier and customer. Both industries are extremely regulated, they have very critical components (for example, patient-specific implants in the medical industry). The enormous complexity and constantly not having room for error promotes greater involvement of the two parties both in the design process, testing phase, and manufacturing of the final product. For that reason, the partnerships from the AM provider and customer are very strong.

Therefore, the following research questions are addressed:

1. How different functions internal and external to the organization collaborate for design for AM?
2. What are the key enablers in successful collaborations for design in aerospace and medical AM projects?

[2] Food and Drug Administration

To achieve the purpose of this thesis a qualitative methodology was applied, constituted exclusively by secondary data. Primary data was intended to be collected through interviews but due to unplanned events mentioned in section 1.2 Study Limitations, that was not possible. The secondary data was based on reviewing relevant literature, based on books, scientific articles, reports and, aerospace, and medical case studies obtained through various AM service providers. The analysis of these cases follows a CIMO-logic framework, a systematic structure review process that helps to contextualize a problem and assess the interventions that lead to successful outcomes. Through this analysis, were identified patterns within Aerospace and Medical cases about what kind of integration and enablers were needed for Design for AM projects. Together with the base theory from the literature review, the main objective of answering the aforementioned research questions was achieved.

1.1 READING GUIDE

This project contains six main sections throughout this thesis. Starting with the first section, which is an introduction of the project and a presentation of the objectives and research questions, acts as the reasoning behind why the project is carried out.

The rest of the thesis is structured as follows:

Chapter 2 (Theoretical framework) - consists of a review of literature relevant to our research area.

Chapter 3 (Methodology) - describes the specific methodology and research approach utilized in this project.

Chapter 4 (Analysis) - is presented with the case studies, analysis, and findings assembled to answer the research questions with applied and operationalized theories.

Chapter 5 (Discussion) - is reflected in what were the practical and theoretical implications as well as final propositions and suggestions for future research in this area.

Chapter 6 (Conclusion) - is explained the relevance and significance of this work, if the adequate answers to the research questions were found and what did the answers tell us.

Chapter 7 (References) - presents what literature is used, who are the authors behind it, and when was it published, it also includes all the industries specific case studies used for the analysis part of this study.

In the following Figure 1, is showcased the study structure:

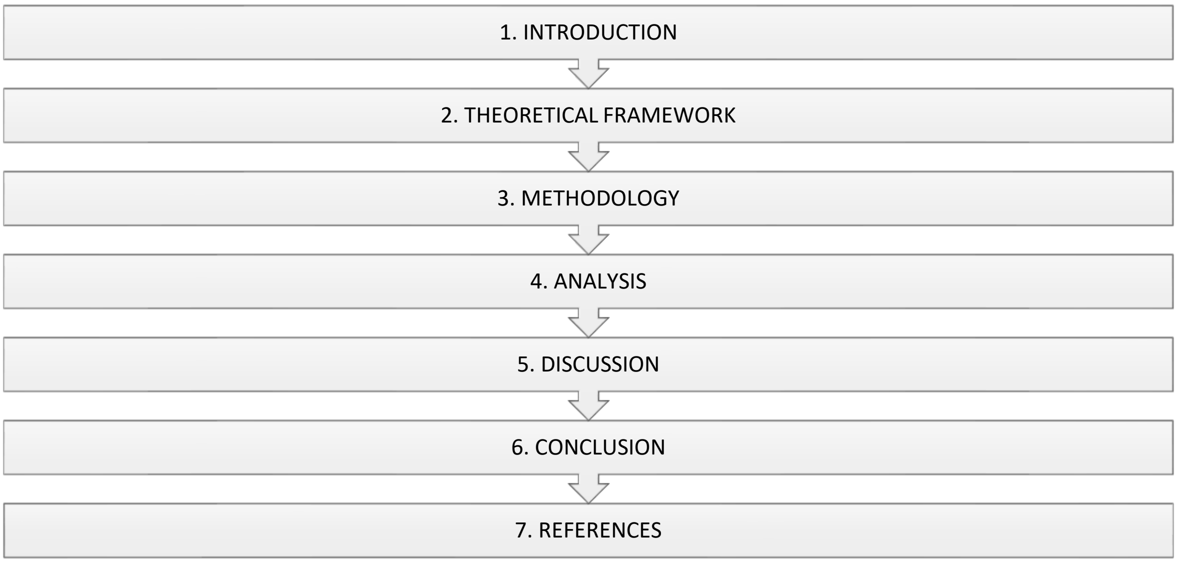

Figure 1 Study structure

1.2 DEMARCATION OF SUBJECT AREA

Demarcations of the thesis should not go unmentioned at this point. This section is presented to highlight some of the delimitations of the project and the further impact of these on the findings and conclusion of the report.

First, when studying a field as vast as the additive manufacturing with such limitations in time and resources, there is the need to create some boundaries. Therefore, the study is actively demarcated to focus on the intriguing topic of supply chain integration for design for additive manufacturing.

This thesis is limited to the study of two industries, the Aerospace and Medical industries. The demarcation was made in collaboration with the supervisor of the project due to his insight into the subject area and the existing lack of academic research on this specific topic. The choice to focus on only these industries was primarily because similar studies were being carried out simultaneously by the supervisor of this thesis, allowing me to highlight the enablers and the specific characteristics of the collaborations in these fields and at the same time, having two industries that allow a cross-industry analysis and reveal their similarities or differences. The study also experienced demarcations in terms of the medical industry, all case studies related to the dental field were excluded, as these were already being a point of research the time this project was suggested and accepted.

More, this study only focusses on finished products and for that reason during the formulation of the search strings identified keywords and synonyms for prototyping were made to be further excluded from the search.

1.3 ABBREVIATIONS

The initial part of this project introduces a list of abbreviations. It includes all the abbreviations and definitions of terms and terminologies used throughout this study.

Abbreviations were used to make it faster to express and understand what was written without constantly repeating the same words. The best given example is Addictive Manufacturing, which is abbreviated to AM, but a greater variety of terms can be found in that section.

2 THEORETICAL FRAMEWORK

The previous section presents the purpose, research questions, objectives of the project, and study limitations. The following theory section consists of a review of literature relevant to the research area. The focus of the literature will be to make an in-depth investigation of the design for manufacturing and additive manufacturing. It will provide knowledge towards discussing and investigating, alongside the qualitative data from the case studies, and will be the foundation for the comparison of both data, creating multiple relations and develop propositions with the findings.

The literature review in this section will go through the subjects of Additive Manufacturing, design for additive manufacturing, design for excellence, supply chain integration for NPD (New Product Development), and supply chain integration for design for X (DfX).

The section ends with a summary in which will be shortly described how the gained knowledge is useful in the context of the research questions and the service provider's case studies.

2.1 FRAMEWORK

Due to the high importance of the literature review in this project, the creation of a framework serves to ensure credibility throughout the findings of the thesis. The framework for the literature review is as shown below in Figure 2. The process is primarily deductive, meaning that the search strings and evaluation of articles and their content were executed according to predefined criteria. The development of the framework is done according to the PRISMA Flow Diagram (Moher et al. n.d.).

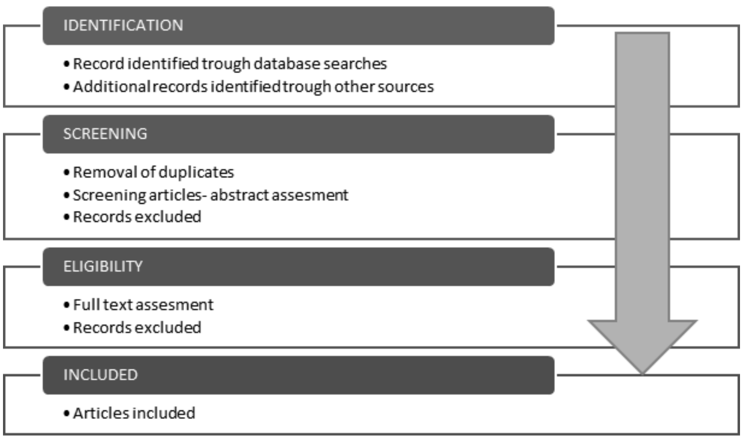

Figure 2 Framework with literature review phases

2.1.1 SCOPE OF THE LITERATURE REVIEW

In order to collect relevant literature from the academic fields, the scope of the literature search needs to be defined. The areas are mainly identified through the process of creating the research questions. Figure 3 shows the conceptual framework of the scope of the project which helps to clarify how these areas intersect.

The identified areas are:

1. Additive Manufacturing
2. Enablers
3. Design

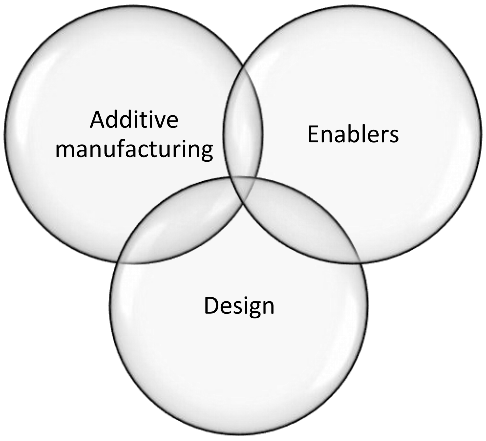

Figure 3 Framework for literature search

2.1.2 LITERATURE SEARCH

This section introduces the formulation of the keywords and search strings applied in the literature search. The keywords and search strings are the foundation for finding the most literature regarding the research questions and the subject of the project.

To access relevant literature, the search strings are executed in two main databases, shown in Table 1. Generally, the databases are comprehensive and known for containing extensive literature regarding the research subjects.

Database	Link (where)	What	Why
ProQuest	Search.proquest.com	Database containing broad literature in humanities, social sciences, natural sciences and medicine	Extensive number of scholarly journals
Scopus	Scopus.com	The largest abstract and citation database of peer-reviewed literature. Fields of science, technology, medicine, social sciences, arts and humanities	Extensive number of scholarly journals

Table 1 Databases used for literature search

The development of the keywords and search strings is done to examine the existing research and knowledge concerning the elements in the scope of the project. The process is mainly done through a brainstorm. The keywords, additional synonyms, and related terms are presented in Table 2 below.

Subjects	Identified synonyms and related keywords
Additive Manufacturing (AM)	"Additive manufacturing" OR "direct manufacturing" OR "3d printing" OR "3-d printing" OR "3d-printing" OR "digital manufacturing" OR "rapid manufacturing" OR "three dimensional printing" OR "three-dimensional printing" OR "freeform fabrication" OR "free form fabrication" OR "additive fabrication" OR "additive production"
Design (D)	design OR "design for" OR layout OR architecture OR pattern
Supply Chain (SC)	logistic OR shipping OR transport OR shipment OR "supply chain" OR "supply-chain" OR "value chain" OR "value-chain" OR "supply network" OR "supply-network" OR SCM OR "supply chain management"
Integration (I)	integration OR "internal integration" OR "external integration" OR "collaboration" OR "collaborations" OR "enablers"
Design for Excellence (DfX)	"design for excellence" OR "DfX" OR "DFX"
New Product Development (NPD)	"new product development" OR NPD

Table 2 Identified keywords and synonyms

2.1.3 RESULT OF SEARCH

From the previously mentioned subjects, suitable search strings are formalized through combinations of some of the keywords and synonyms. While formulating the first search strings when using all the synonyms and related keywords for the search, generated a result of hundreds of articles obtained. For example, the first search approach has created a string combining (SC + AM + D) which resulted in more than 200 scholarly journals obtained.

For the final search strings, a different approach was used, the results were limited by using shorter search strings and at the same time merging keywords from different subjects. This enables more study-specific results along with a straightforward literature review process. Lastly, the search strings were executed in the databases and the numbers of articles found are presented in the following table.

Subject area	Search string	Database
String 1: AM and D and DfX	(“Additive manufacturing” OR “direct manufacturing” OR “3d printing” OR “3-d printing” OR “3d-printing” OR “digital manufacturing” OR “rapid manufacturing” OR “three dimensional printing” OR “three-dimensional printing”) AND (design OR “design for” OR layout OR architecture OR pattern) AND (“design for excellence” OR “DfX” OR “DFX”)	P= 6 S= 16
String 2: SC and I and NPD	("supply chain integration") AND ("new product development" OR NPD)	P= 13 S= 18
String 3: SC and I and DfX	("supply chain integration") AND (“design for excellence” OR “DfX” OR “DFX”)	P= 4 S= 5
String 4: SC and I and DfAM	("supply chain integration") AND ("design for additive manufacturing" OR "DfAM" OR "design for 3D Printing")	P= 2 S= 2
Total		66

Table 3 Applied search strings (P= ProQuest, S= Scopus)

In the databases, the filters applied to the searches are as follows:

- Only scholarly journals
- Published after the year 2000
- Only search fields: “abstract, title, keywords” or “No full-text” or similar

These filters are applied to restrict the results and make sure the articles have the right fit for the literature review.

From the total 66 articles the search and after a systematic review (selection process), by removing duplicates and abstract assessment, 15 articles are obtained. Through-out the report, this literature will be used as references and background knowledge.

Search strings	**Phases (Following the literature framework)**			
	1st Records identified	2nd Removal of duplicates	3rd Abstract assessment	4th Articles included
String 1: AM and D and DfX	22	22	13	8
String 2: SC and I and NPD	31	28	11	3
String 3: SC and I and DfX	9	7	4	1
String 4: SC and I and DfAM	4	4	2	1
Total	66	61	30	13
Additional records				2
Total records				15

Table 4 Literature inclusion and exclusion results

2.2 LITERATURE LEARNINGS

This section will introduce the main learnings derived from the literature review being design for additive manufacturing, design for excellence, supply chain integration for new product development, supply chain integration for design for X, and supply chain integration for design for AM. Furthermore, it will provide knowledge towards discussing and investigating all related factors influencing the collaborations for design for AM projects.

2.2.1 DESIGN FOR ADDITIVE MANUFACTURING

Design for additive manufacturing "*... is when designers seek to create a product design that takes advantage of the unique capabilities of AM"* (Diegel, Nordin, and Motte 2019a). In DfAM, it's not simply re-designing the existing part for AM, the process constraints of the AM technology are always respected. Is Diegel, Nordin, and Motte (2019b) opinion, when designing products designers should keep in mind:

- Shape complexity
- Hierarchical complexity
- Functional complexity
- Material complexity

The AM processes build time can be significantly reduced and become more applicable when the design parameters and process are correctly adjusted (Hallmann, Schleich, and Wartzack 2019).

In DfAM, a function-driven design strategy neglects the conventional design rules and the component is designed accordingly to is functions and requirement of the AM process. Performance increase in efficiency, weight and reduction of parts number are the main benefits (Klahn, Leutenecker, and Meboldt 2015).

In such regulated industries as aerospace, the qualification of products can be very challenging. Therefore, 3D printing providers must use their AM knowledge to define the product requirements and suitability for AM (Dordlofva 2020). A systematic search can be performed either on an existing product or during new product development (Klahn, Leutenecker, and Meboldt 2014).

According to Dordlofva et al. (2019), customer satisfaction is achieved when aiming towards the cost and lead time reduction, show product functional and technical compliance, and compliance in standards/regulations. Similarly, design organization satisfaction should aim for compliance with requirements on reliability and internal specifications and increase the adaptability of product designs for future business opportunities.

2.2.2 DESIGN FOR EXCELLENCE

In Design for Excellence (DfX), the "excellence" suggests that a product could become perfect through continuous improvements (M. C. Chiu and Lin 2016). The variable X represents product aspects such as functionality, manufacturability, safety, quality, or serviceability and can have multiple possible values. It implies a consideration of a specific factor when designing a product for performance improvement (Dordlofva et al. 2019).

2.2.3 SUPPLY CHAIN INTEGRATION FOR NPD, DESIGN FOR X AND DESIGN FOR AM

New product development (NPD) is an important process used by companies to achieve a competitive advantage in the market (Khan, Christopher, and Creazza 2012).

Lau, Yam, and Tang (2007) affirm that new product development performance was driven by the coordination among marketing, manufacturing, and R&D departments. First-tier supplier involvement in co-design activities has a positive impact on NPD and project performances in terms of cost, quality, and lead-times (Khan, Christopher, and Creazza 2012). Although a high supplier integration in NPD can have negative effects, excessive integration may lead to less new product development possibly due to resource limitations (Parente, Baack, and Hahn 2011).

The concept of design for X has been developed at the design stage to reduce the total cost and lead-time of the product (M.-C. Chiu and Okudan 2011). When implementing integrated DfX techniques it's necessary to know beforehand the impact in the design process. DFX implementation should not be based on voluntary action but rather on a mandatory action. Design for X techniques expanded beyond production to the entire supply chain and enabled consideration of the impact that design has on the economy, ecology, social, and the health of the company. The application of DFX should be explored simultaneously for an improved understanding of product design (Benabdellah et al. 2019)

The literature review identified a gap in supply chain integration for DfAM literature. It was previously emphasized the importance of early customer involvement at the product design stage. According to Chiu and Lin (2016), the employment of AM technology improves the supply chain (SC) performance in terms of decreasing average lead time and total cost. It breaks the barrier of integral and modular product architectures so that the efficiency of production can be further upgraded. The SC structure becomes flat due to the simplicity of the manufacturing process. This reduces the complexity of management and increases the flexibility as well as the resilience of SC operation.

2.3 LITERATURE GAP

Following the literature assessment, a gap of literature is identified regarding supply chain integration for design for AM. Intending to answer the research questions, this gap is a subject of investigation in this thesis.

2.4 SUMMARY

Throughout this chapter, the literature review framework and the literature findings have been presented towards subjects such design for AM and supply chain integration.

The identified literature gap presents a justification for this study as the investigation of collaborations in design for AM cases is essential to answer the research questions. The literature review also highlights elements such as supply chain integration for new product development and design for excellence.

3 METHODOLOGY

This chapter will present three essential elements of the project; the research design, the data collection, and the data analysis. This chapter further presents an outline of the methodology and approaches utilized throughout the project in the respective sections.

The overarching design of the research is developed inspired by the research onion. The research philosophy in this project is positivism, which is characterized by a structured data collection method utilized in this project as well as a focus on the causality of the phenomena (Saunders, Lewis, and Thornhill 2019). The research approach is deductive, data collection is used to evaluate propositions or hypotheses related to an existing theory.

The research strategy and the techniques and procedures are elaborated in the following sections. The research design is showed in Figure 4.

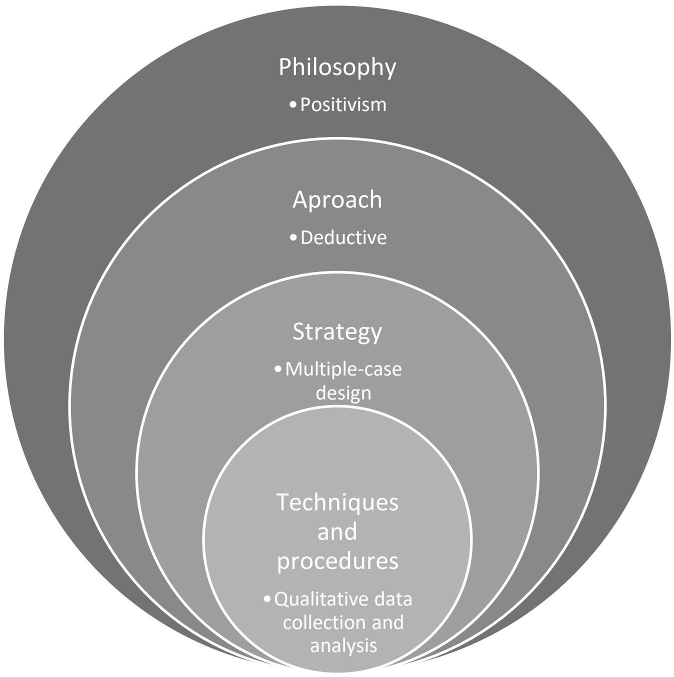

Figure 4 The research onion in the context of this project

3.1 RESEARCH DESIGN

A multiple-case design is chosen as a research methodology to adequately develop an in-depth understanding of the collaborations for design in aerospace and medical AM projects. As is common to this type of design (Mills, Durepos, and Wiebe 2012), each case was initially carefully exanimated as a single case, and after the data was organized a cross-case comparison was developed.

A literature review of relevant literature revealed that there was no substantial empirical research on supply chain integration for design for AM. Therefore, a secondary review analysis based on available material from AM service providers databases was carried out to develop a practical understanding of the key enablers in successful collaborations for design for AM.

The chosen deductive research approach allowed us to explain the relationships between collaborations. From the literature, I deduced the hypothesis of a higher external collaboration between supplier and customer in this kind of industry. The findings from data analysis enabled to confirm or reject this theory.

The CIMO-logic framework was selected to assess the gathered data. By following this framework I was able to determine the Context (C) in which Interventions (I) lead to the Outcomes (O) through specific Mechanisms (M). (Khajavi and Holmström 2018). With the implementation of this approach to the secondary data analysis I was able to perceive how in a specific situation, the intervention leads to the achieved benefits.

Further, in analysis, the software NVivo was used as it provides a range of tools for handling data from document analysis, literature reviews, and other qualitative research methods (Davidson 2018). It allowed me to create links in the texts and uncover relationships among nodes from different cases. Thus, the relationship between integration and enablers on outcomes and the influence by the context and possibly the intervention needed.

The replicability in this project is robust, as all the procedures, data collection, and analysis methods are presented.

This study was limited in time and resources. Were found many sources for this type of design for AM cases but due to the time limitation I decided to focus only on the ones considered most reliable and that assured a greater data quality to secure validity to the study.

3.2 DATA COLLECTION

Throughout this thesis, multiple data collection methods are used. These methods are utilized to collect the desired secondary data required to conduct the investigation. The methods and the type of data are displayed in Table 5.

Method	Quantitative	Qualitative
Academic articles		✓
Databases		✓

Table 5 Data collection methods

3.2.1 SECONDARY DATA

Due to unpredictable events explained in 5.3 STUDY LIMITATIONS, this project had a constrain in primary data collection, as it was not possible to collect data by executing semi-structured interviews with AM service providers and costumers. Therefore, only secondary qualitative data was used. The secondary qualitative data collection method was academic articles accumulated from the previous explained literature search; and 3d printing service providers databases.

3.2.1.1 CASES STUDIES COLLECTION

This project relies on qualitative data from case studies gathered from additive manufacturing service provider databases. These types of companies usually provide free access to numerous success stories of their AM technology in product development /design. In section 7.2 CASE STUDIES SOURCES, is available the links from all the databases used in this project. Over this research, was set an industry constraint due to the focus in the Aerospace and Medical industries.

3.2.1.2 LITERATURE REVIEW

Previously explained in chapter 2 THEORETICAL FRAMEWORK, a systematic literature review was conducted to assess existing material and create the body of knowledge that was to be used in the context of the study to investigate the problem statement. Further, the literature review identified gaps in the current literature and will help drive the study to generate new academic knowledge. The literature review includes books, scientific articles found through the search engines ProQuest and Scopus. The literature reviewed was created between 2006 and 2020.

3.3 DATA ANALYSIS

As stated in the research design, this project is designed as a secondary data analysis using multiple qualitative case studies. The case review follows a CIMO-logic framework The respective data analysis is presented in chapter 4 ANALYSIS of this report to increase visibility in where the respective analyses are performed.

3.3.1 CIMO-LOGIC (CONTEXT, INTERVENTION, MECHANISM, OUTCOME)

In this section its briefly introduced the framework applied in the review of the selected cases. Following a CIMO-logic it combines the contextualization of the problem with certain intervention types performed to solve that problem, which follows determined generative mechanisms, to achieve the expected outcomes (Costa, Soares, and de Sousa 2018).

According to (Colicchia and Strozzi 2012), for a successful systematic literature review all the phases of a CIMO-logic, (Context, Intervention, Mechanisms, and Outcome) need to be performed. The following

Figure 5 helps to understand the framework and the questions to be answered in each part of the process.

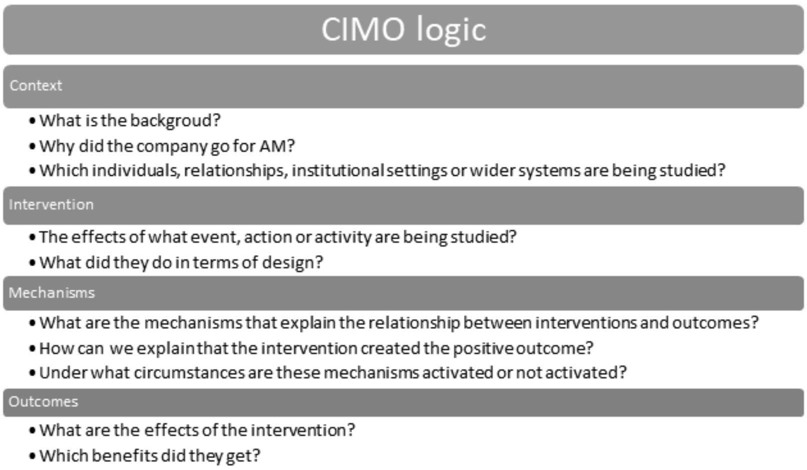

Figure 5 CIMO logic framework elements

The objective of using a CIMO-logic framework for this study analysis is to understand the link between the initial problem and the final obtained benefits. What were the interventions and mechanisms applied in these cases that made the several companies choose to manufacture their products with Additive Manufacturing technologies and the enablers to the partnerships with the AM service providers? The next chapter 4 ANALYSIS will showcase the findings from a structured review of medical and aerospace industry cases.

4 ANALYSIS

The purpose of this chapter is to showcase all the relevant data that goes into review. As not all results are equally important, it will be used to emphasize on the key findings of this study.

The initial part of the analysis 4.1 CASES SELECTION, will present a list of the cases and how they were selected. Further analysis is executed according to the CIMO-logic framework introduced in 3.3.1 CIMO-LOGIC (CONTEXT, INTERVENTION, MECHANISM, OUTCOME), and the results will be divided by Aerospace and Medical cases The qualitative data analysis software NVivo is used to easily identify patterns within the cases on what kind of integration and enablers were needed for Design for AM projects and the relationship between those to the context, intervention and respective outcomes. It is important to note that this chapter seeks to investigate the cases concerning the following research questions:

RQ1: How different functions internal and external to the organization collaborate for design for AM?

RQ2: What are the key enablers in successful collaborations for design in aerospace and medical AM projects?

4.1 CASES SELECTION

This section presents the selected cases for analysis. This project has seven sources, the AM service providers 3T AM, EOS, SLM Solutions Group and Materialise. Initially, they were retrieved for examination more than one hundred cases from the medical and aerospace industries. Resulting from a systematic review, where were excluded all non-relevant cases (such as dental cases) or where too much data was missing, a total of 35 cases were used in this analysis chapter.

To facilitate the analysis of such a large number of cases, the articles were coded. The full title of the cases can be accessed in the bibliography, section 7.3 CASE STUDIES. The code follows an **AMx_yz** structure, where AM refers to additive manufacturing cases and the variables x, y and z represent:

X – General case number (from 01 to 35)

Y – Application industry (A=Aerospace, M =Medical)

Z – Case number in a specific application industry

The subsequent Table 6 presents the list of all the selected cases, as well as the service provider where they were retrieved and the respective application industry. More information related to the company and the respective case can be seen in Appendix A.

Case identification	Service provider	Application Industry	Case identification	Service provider	Application Industry
AM01_A1	3T AM	Aerospace	**AM19_M7**	EOS	Medical
AM02_A2	3T AM	Aerospace	**AM20_M8**	EOS	Medical
AM03_A3	3T AM	Aerospace	**AM21_M9**	EOS	Medical
AM04_M1	3T AM	Medical	**AM22_M10**	EOS	Medical
AM05_A4	EOS	Aerospace	**AM23_A13**	SLM SOLUTIONS	Aerospace
AM06_A5	EOS	Aerospace	**AM24_A14**	SLM SOLUTIONS	Aerospace
AM07_A6	EOS	Aerospace	**AM25_A15**	SLM SOLUTIONS	Aerospace
AM08_A7	EOS	Aerospace	**AM26_M11**	SLM SOLUTIONS	Medical
AM09_A8	EOS	Aerospace	**AM27_A16**	MATERIALISE	Aerospace
AM10_A9	EOS	Aerospace	**AM28_A17**	MATERIALISE	Aerospace
AM11_A10	EOS	Aerospace	**AM29_A18**	MATERIALISE	Aerospace
AM12_A11	EOS	Aerospace	**AM30_M12**	MATERIALISE	Medical
AM13_A12	EOS	Aerospace	**AM31_M13**	MATERIALISE	Medical
AM14_M2	EOS	Medical	**AM32_M14**	MATERIALISE	Medical
AM15_M3	EOS	Medical	**AM33_M15**	MATERIALISE	Medical
AM16_M4	EOS	Medical	**AM34_M16**	MATERIALISE	Medical
AM17_M5	EOS	Medical	**AM35_M17**	MATERIALISE	Medical
AM18_M6	EOS	Medical			

Table 6 Selected case studies for analysis

4.2 AEROSPACE INDUSTRY CIMO

In this section, the focus goes to the CIMO analysis of all the cases from the Aerospace industry. The obtained results were composed and can be seen in the following Table 7.

Id	Context	Intervention	Mechanism	Outcome
AM01_A1	Re-design a turbine arm mount	Using AM technology focused on a low mass production	Working closely on the original design with the CAD team	Weight reduction Assembly into a Single Part More efficient geometry
AM02_A2	Develop a rocket engine	Exploiting AM's ability to build in Copper	Collaborative partnership results in a world first for the space industry	Cost reduction Improved lifetime
AM03_A3	Replace an airplane small breather pipe from a cabin window	Designed the replacement breather pipes	Regional Aircraft worked with 3T-am to develop the product for production	Cost reduction (60%)

AM05_A4	Develop an extremely lightweight and robust antenna bracket for Sentinel satellites	Collaboration in design and production of the antenna bracket	Production of a component using additive manufacturing, which, by virtue of to its complex structures, fulfils all requirements of weight and stability	Improved rigidity (30%) Weight reduction (40%) Industry accredited product
AM06_A5	Manufacturing of aerospace parts across the supply chain	Performed a streamline Life Cycle Assessment (SLCA)	Use of DMLS to allow the use of different materials, optimised design and more energy efficient processes under consideration of a holistic analysis that include ed sourcing of raw material. Collaborative partnership	Material reduction Sustainable Continuous collaboration
AM07_A6	Substitute a conventional primary flight control hydraulic component with an additively manufactured part – fulfilling all certification requirements for flight	Hydraulic structures were identified, and auxiliary sections were removed. The positioning of the main components was reconsidered considering their installation space and interface requirements with the aim of optimizing intelligent, short connection lines.	Collaborative partnership with different sources of knowledge	Weight reduction (35%) Simplified (10 parts eliminated) Fulfil all certification requirements for flight Efficient
AM08_A7	Production of an injection head for rocket engines with as few components as possible and lower unit costs	Production pilot test with a new optimized material and AM technology	Functional integration in design 4-laser technology allowed the propulsion module component to be manufactured up to four times as fast	Simplified (One component instead of 248) Cost reduction (50%) Production time reduced
AM09_A8	Production of a cable routing mount for a camera in the vertical stabilizer of the A350	Analysis of the existing, conventionally produced component in terms of the upcoming manufacturing process	Thanks to the cooperation between customer and supplier, it was possible to develop a component optimized for additive manufacturing that fully exploits the design freedom afforded by DMLS technology while at the same time taking account of its restrictions	Simplified (1 part instead of 30 components) Lead time reduction (90%) Weight reduction (30%)
AM10_A9	Cost-effective production of optimized retaining brackets for the connection of components in telecommunicat ion satellites	After design and process were established, the engineers loaded the 3D construction plans from the CAD software into the production machine	Design improvement, so the entire workpiece can be manufactured in a single step.	Cost reduction (20%) Weight reduction (300g) Pioneering role

AM11_A10	Production of robust probes for measuring speed and temperature in turbo engines	Modelling the components attaching great importance to minimizing the number of possible disruptive factors and their effects Extensive post-production treatment	Additive manufacture of extremely robust and at the same time thin probes featuring a long service life and precise measurements Implement special functionally integrated designs Post-production treatment to optimize product quality	Robustness Low-maintenance Production time reduced
AM12_A11	Production of flight-certified components	Prove machine and its processing capabilities in order to certify the AM technology for use	Collaboration between partners in constant design review and quality testing	Optimized Efficient Cost & lead time reduction in post-processing Economical (plastic powder can be recycled)
AM13_A12	Manufacture of turbines borescope bosses	The company developed a new process chain, which has been approved and integrated into the manufacturing system.	The entire manufacturing process is underpinned by a control system specifically developed by MTU. Online monitoring captures each individual production step and layer. In addition, new quality assurance procedures were introduced, such as optical tomography.	Freedom of design Lead time reduction Economical (reduces costs of development and production)
AM23_A13	Development of a hydraulic valve block	The hydraulic valve block was developed by VTT and Nurmi Cylinders, with a design optimized to take full advantage of the benefits of 3D printing	AM opens new business opportunities by freeing design from the restrictions of traditional manufacturing processes, enabling customization and speeding up product time to-market This technology also enables small, one-off production runs, which remove the additional costs typically associated with customization	Size reduction (76%) Weight reduction Material reduction
AM24_A14	Production of a rocket propulsion engine	The internal structure developed by CellCore is the fundamental element of the engine and cannot be manufactured by traditional methods.	The single-piece rocket propulsion engine, combining the injector and thrust chamber, reduces numerous individual components into one, with multi-functional lightweight construction achievable only with the selective laser melting process	Cost reduction Lead time reduction Weight reduction Competitiveness
AM25_A15	Production of a gooseneck bracket from a flap actuation mechanism	The gooseneck bracket was redesigned for with the design principals of Design for Additive Manufacturing (DfAM), utilizing topology optimization.	In the course of this optimization project ASCO and SLM Solutions have chosen a collaborative approach to achieve the best design of the new Gooseneck Bracket. SLM® application engineers were involved in the review of the different design steps to ensure manufacturability.	Weight reduction (31%) Simplified (1 part instead of 3) Lead time reduction (42%)

AM27_A16	Production of spacer panels of commercial aircraft cabins	The spacer panels are produced by additive manufacturing and then painted to Airbus cabin requirements, all using flame-retardant Airbus-approved materials	Innovating together in design and production processes with supplier's software and knowhow of AM, but also by seamlessly integrating Airbus's own way of working	Weight reduction (15%) Certified components Lead time
AM28_A17	Manufacturing Flight-Ready Parts for an aircraft	In preparation to re-launch the serial production of this aircraft type, Supply Chain and Engineering at 328 are in a constant process of streamlining manufacturing processes and identifying cost drivers.	For reliability and quality assurance, every production run must be exactingly consistent and traceable. Materialise Streamics ensures a transparent software overview of the production process. Materialise holds certifications that qualify to manufacture end-use parts for the aeronautics and aerospace industries, and that makes the Certified Additive Manufacturing process the perfect fit for 328.	Cost reduction Lead time reduction
AM29_A18	Re-design of component used in the aerospace sector to transfer high mechanical loads in structures like satellites	With a cleverly optimized design produced through Metal 3D Printing	With AM, the interior space of objects can be hollowed out or designed with lightweight structures, using material only where necessary. Engineers at. Using the advanced techniques of topology optimization and lattice structured design, the team was able to do mass reduction	Weight reduction (66%) Material improvement Increased lifetime Cost reduction

Table 7 Aerospace CIMO analysis

The context of the cases varies from the production of aircrafts engine components, satellite parts, a hydraulic valve block to panels of commercial aircraft cabins. What stands out the most from this column is the fact that many companies decide to go for AM because they wanted to re-design their pre-existing products. It is known the advantages of AM technologies of producing parts with complex geometries and little wastage. From the outcomes, it was achieved benefits of weight, cost, and lead time reduction, as well as product simplification. As parts that previously required assembly from multiple pieces can be fabricated as a single object.

Collaborative partnerships between customer and supplier were several times mentioned in during the intervention and mechanisms phases.

4.2.1 THE AEROSPACE INDUSTRY PATTERN

Apart from the CIMO analysis, the cases were analysed concerning the study research questions. This process allows us to identify several functions external and internal to the organization that collaborates for design for AM. Many companies referred to the external collaboration with the supplier as a very important aspect to the success of their projects, the exchange of knowledge and constant support during the different phases of the design and production of the final components were big enablers for the accomplishment of such outcomes. In some cases, it is only mentioned that there existed some type of collaboration during the project, while on others, it is explicitly attributed to supplier support with the topology optimization, shared knowledge about AM processes, knowledge about AM materials, and knowledge regarding AM software.

In terms of internal enablers, only a few cases referred to internal cross-functional integration gained when engineers who've acquired experience with the material and the process communicate to teams with other functions, and those teams start to incorporate additive manufactured hardware into their assemblies or the granted ability to integrate functions in a production chain. Also, having internal capabilities such as design knowledge in case AM29_A18, played a role in enhancing the final product's overall performance. Besides, during this analysis other factors were observed but were not counted for this study due to its lack of relevance (Appendix B).

Using the qualitative data analysis software NVivo, we can code into nodes all the material referent to the CIMO analysis and integration enablers, and later run the matrix coding tool to create a matrix that shows the coding intersections between both parameters (Table 8).

	Context	Intervention	Mechanisms	Outcomes
Supplier collaboration	0	3	5	2
Supplier helping with the topology optimization	1	4	2	1
Supplier providing knowledge about AM materials	0	0	0	0
Supplier providing knowledge about AM processes	0	1	1	1
Supplier providing knowledge about AM software	0	0	1	1
Internal capabilities	0	0	0	0
Internal cross-functional integration	0	0	0	0

Table 8 Matrix with integration enablers mentioned in the Aerospace CIMO's analysis

Looking at the numbers from Table 8, it is noticeable the incidence of the external enabler's references in the different CIMO phases, in contrast to the non-existent of internal.

Therefore, it became evident a pattern within Aerospace cases about what kind of integration and enablers were needed for Design for AM. The external collaborations are of high relevance to the customer, they rely on the support and the knowledge share of the AM technology from the service providers as they don't have internal resources to implement this type of production by themselves.

4.2.2 KEY ENABLERS IN THE AEROSPACE INDUSTRY

Established that the external functions to the organization, such as collaborations between supplier and customer, are the main drivers for design for AM integration, we need to define what are the key enablers in these particular cases from the Aerospace industry regarding the context, interventions, and outcomes they got. Thus, by using the matrix coding tool in NVivo, it allowed the display in a structured format the cases where internal and external integration enablers were mentioned. The following Table 9 shows the number of references to DfAM integration enablers.

Aerospace	Supplier collaboration	Collaboration for process	Collaboration for material	Collaboration in topology optimization	Collaboration in software	Internal capabilities	Internal cross-functional integration
(AM01_A1)	2	0	0	2	0	0	0
(AM02_A2)	0	0	0	0	0	0	0
(AM03_A3)	0	0	0	0	0	0	0
(AM05_A4)	2	1	0	1	0	0	2
(AM06_A5)	2	1	0	1	0	0	0
(AM07_A6)	2	1	0	0	0	0	0
(AM08_A7)	1	1	0	0	0	0	0
(AM09_A8)	0	0	0	0	0	1	0
(AM10_A9)	0	0	0	0	0	0	0
(AM11_A10)	1	0	0	0	0	0	0
(AM12_A11)	2	1	0	0	0	0	1
(AM13_A12)	2	0	0	1	0	0	0
(AM23_A13)	0	0	0	0	0	0	0
(AM24_A14)	2	1	0	1	0	0	0
(AM25_A15)	2	1	0	1	0	0	0
(AM27_A16)	2	1	0	0	1	0	0
(AM28_A17)	0	0	0	0	0	0	0
(AM29_A18)	1	0	0	1	0	1	0

Table 9 Aerospace cases where internal and external integration enablers were mentioned

As expected, Table 9 shows a greater number of mentions to supplier collaborations than to the internal factors. Out of a total of eighteen cases analysed, twelve of them referenced in their report at least one type of external enabler.

Inspecting the collaboration in knowledge share regarding the AM processes, there is a reference in eight cases (AM05_A4, AM06_A5, AM07_A6, AM08_A7, AM12_A11, AM24_A14, AM25_A15, and AM27_A16). Most of these case studies share a similar background, the companies seek to find a better solution to develop their existing products instead of using conventional manufacturing processes, while fulfilling all strict certification requirements present in this type of flight components. Some of the interventions were, performing a streamline Life Cycle Assessment (SLCA), analysis of the existing conventionally produced component in terms of the upcoming manufacturing process, or prove machine and its processing capabilities in order to certify the AM technology for use. For all these contexts and interventions, the companies rely on the knowledge from the service provider on AM technology, as this is something completely new for them. The relationship of this enabler on the outcomes is therefore influenced by the context and the intervention needed. Outcomes such as weight and cost reduction, industry certified product, and competitiveness were obtained.

Regarding collaborations for material decisions, there isn't any evidence in the text that this is needed. It suggests that companies from this industry have already done a material assessment and this can be used in AM. From Appendix C, the materials most used are titanium, aluminium and nickel alloys.

Similarly to the enabler of collaboration for AM processes, there is a reference for collaboration in topology optimization in seven cases (AM01_A1, AM05_A4, AM06_A5, AM13_A12, AM24_A14, AM25_A15, and AM29_A18). The contexts imply the implementation of completely new technology or the attempts of optimizing their products through a re-design process. For that reason, companies explore the supplier know-how in design for AM, leading to outcomes of freedom of design, improved rigidity, and product simplification (1 component instead of multiple parts).

Highlighted in only one case (AM27_A16), the collaboration for software enabler shows a weak relationship between context and outcomes. Thus, in this study, it is not considered the presence of any pattern for this enabler in the aerospace industry.

Due to a low amount of references in the aerospace cases to the internal enablers, internal capabilities, and internal cross-functional integration, can't be created a strong relationship between these and the project's successful outcomes.

4.3 MEDICAL INDUSTRY ANALYSIS

In this section is carried out the same CIMO analysis procedure as before, this time will be handled all the collected cases from the Medical industry. The obtained results were composed and can be seen in the following Table 10.

Id	Context	Intervention	Mechanism	Outcome
AM04_M1	Improve alloplastic facial implant	3T-am produced the initial functional design for the implant in titanium	Titanium AM implant could overcome some of the problems associated with existing implant materials Working in partnership with 3T-am	Customization Accurate operative fit
AM14_M2	Production of implants for cranial, jaw and facial bones	Explore the market and analyse what was available	The team used the results of the computed tomography examination, where all the necessary contouring information is recorded in detail. The data transformation to a CAD program and the design and manufacture of the implant all took place at CEIT.	Patient-specific customization Efficient Innovative Certification
AM15_M3	Development and manufacture of a precision-fit implant for the cranial area with permeability for liquids and heat dissipation	The doctors provided the medical technology experts from Novax DMA and Alphaform with requirements to meet along the way	Alphaform applied a multi-step process of abrasive and mechanical cleaning, rinsing, and ultrasound in order to arrive at the medically required level of purity Analyses have confirmed that the implant produced through Additive Manufacturing fulfilled the necessary requirements to stabilize and protect the patient‘s skull.	Optimization Stable Innovation
AM16_M4	Demand grow in patient-specific solutions in spinal fusion surgery	Anatomics has developed an innovative solution called SpineBox™ - a customized kit that uses individual patient CT scan data to create patient-specific devices and pre-plan the selection of spinal fusion hardware.	Using Computed Tomography (CT) patient scan data together with custom planning software developed by Anatomics, a patient-specific solution involving screws, rods and an intervertebral spacer (fusion cage) is designed for each MIS TLIF surgery.	Workflow efficiency Lead time reduction (17%) Radiation exposure reduction (38.5%)
AM17_M5	Manufacturing of STarFix patient-matched frameless stereotactic fixtures	Used a planning software with inputs that create a custom-formed stereotactic guide that attaches precisely to the anchors, aligning the microdrive for recording and DBS lead placement.	Following the parameters of an intelligent, independent solid model provided by the planning software, the fixture is “grown” inside the FORMIGA P 100 in only a matter of hours using PA 2201 polyamide powder Parts consolidation enabled by laser sintering has allowed FHC to fine-tune the STarFix design, reducing assembly time in the OR.	Precision Improved functionality Economic (less material and faster manufacturing turnaround times)

AM18_M6	Development of two patient-specific facial implants for accident victim	Team uses 3D Modelling software, to create a 3D model of patient's anatomy depicting the defect, analyse and design the custom implants required to camouflage & correct the misalignment.	Application of 3D modelling helps to change the way surgeons plan and execute post trauma surgeries with patient specific implants. Customized implant designs were reviewed and endorsed by the surgeon	Lead time reduction Economic (less power consumption) Shorter surgery procedure, faster healing process and great aesthetic result
AM19_M7	Production of FDA approved cranial implants	Speedy manufacturing of individual cranial implants made of PEKK on an EOSINT P 800 by EOS.	After intense navigation of regulatory hurdles, it was possible to start creating of a patient specific cranial implant The customizable implant made of the plastic material PEKK is designed to restore voids in the skull caused by trauma or disease	Customization Osteoconductive Cost reduction Integrated (self-contained production and supply chain)
AM20_M8	Design and production of patient specific complex Orthoses	Construction of individually tailored orthoses for patients, using industrial 3D printing performed with the EOS P 396	Additive manufacturing enables plus medical OT to produce aids of the highest quality using a new approach. Complex structures can be accommodated without problem. It is also possible to incorporate varying material thicknesses within an orthosis, for instance to allow certain areas to be either flexible or stiff.	Freedom of design Weight reduction Reproducibility Standardisation
AM21_M9	Development of tracheal splints to treat a congenital breathing condition called tracheobronchomalasia	Usage of Computer-aided design (CAD) to speed up the engineering side and provide cost-effective, patient-specific production.	A research collaboration between the University of Michigan, its associated hospital, and EOS, based on the use of a FORMIGA P 100. Collaborative partnership from different expertise	Patient specific customization Cost-effective Lead time reduction
AM22_M10	Developing customised leg prosthesis for a cat after successful cancer treatment	Solution Manufacturing of prosthesis with surface structures that promote bone ingrowth.	Design started with 3D data from CT scans of Cyrano's good and bad hind legs. 3D design models of the implant components were made using MIMICS software from Materialise. The EOS technology not only gives design freedom for orthopaedic implants, also offers the means to build Osseo integrated surfaces directly into the part.	Customization Biocompatible and resilient Design complexity

AM26_M11	Case of post-traumatic zygomatic deficiency	Fine-cut CT scanning of the region with 3-dimensional (3D) reconstruction was performed.	Because a full density titanium SLM implant would have been too heavy for implantation, was decided to produce an implant in the form of a shell that was supported by the residual bone and fixation rods. SLM® is one of the CAD/CAM techniques that allows for the production of porous titanium parts that mimic bone structure.	Material quality Productivity increased
AM30_M12	Baby with severe tracheobronchomalacia	Development of a bioresorbable device specially designed splint for the baby	With the collaboration of the two sides, they were able to make the custom-designed, custom-fabricated device using high-resolution imaging and computer-aided design.	Life-saving splint implementation
AM31_M13	Patient was suffering from a Paprosky type 3B acetabular defect	Use a 3D printing to design an implant that fully matches the patient anatomy	The intricate porous structure on the back of the aMace implant, that enables bone ingrowth, is another feature that can easily be achieved using 3D printing. The planning and the custom fit was the added value of the solution, as both result in a stable reconstruction even with the missing bone super cranially.	Successful Life-transforming hip surgery and independency gain
AM32_M14	Medical team is treating patients with structural and congenital heart defects	Create patient-specific Right Ventricular Outflow Tract (RVOT) models to further 3D print	Clinical engineers at Materialise used the Mimics Innovation Suite to produce the 3D-printed models of the patient's complex RVOT. This digital model enabled them to analyse the ovality, deformities and presumed uneven tensile parts of the patient's right ventricular track	Customization Lead time reduction Recovery time reduction
AM33_M15	Baby was born with a complex form of congenital heart disease	Use 3D printing technology to create a replica of the baby's heart	An extremely low dose chest CT scan was acquired to better understand the complex 3D relationships of the heart and defects. With the 3D-printed model in hand, the team of clinicians found an ideal solution for repairing all of the defects during one procedure, instead of three or four surgeries	Improved clinical condition
AM34_M16	Six-year-old with a malignant tumour in her upper left leg need to be operated with the utmost precision	Create a 3D reconstruction from MRI imaging, which was then printed to create an exact copy of the bone	Based on the virtual 3D model, the team formulated a surgical plan with Dr. Sys with guides that enabled her to operate with the utmost precision.	Precision Customization
AM35_M17	Re-design hearing aid manufacturing process	An audiologist takes an impression of the patient's ear canal, the impression is scanned, and the digital file is uploaded to the hearing-aid manufacturer	Thanks to RSM, it was possible to put a new digitized and automated process in place, saving time, effort, and resulting in a more comfortable, acoustically optimized hearing aid.	Lead time reduction Replicability Simplified

Table 10 Medical CIMO analysis

In the medical industry, involves cases backgrounds where there is the need of re-designing hearing aid manufacturing process, production of FDA approved implants, including the production of implants for cranial, jaw and facial bones, treating patients with structural and congenital heart defects, to a Baby born with a complex form of congenital heart disease. The main aspects of these projects are the need for patient-specific implants, components with high geometric complexity, need to use biocompatible materials to reduce some of the problems associated with existing implant materials (including extrusion, migration, foreign body reaction, and infection), and overcome many regulatory hurdles. What stands out the most from this column is the fact that those who demand these services can go from small teams of clinicians, universities partnerships, to companies with the focus on biomedical engineering services. However, a mutual aspect of these projects is the objective of manufacturing singular or low volume niche products. Commonly, they are only enrolled in these projects small of highly specialized teams, so, the role of a partner in the medical industry can be very important for their success. From the outcomes, it was achieved benefits in terms of cost reduction, customization, lead time reduction, precision, and product certification. 3D printing makes it possible to create very specific and complex shapes. Therefore, this is an ideal technique to design an implant that fully matches the patient anatomy.

4.3.1 THE MEDICAL INDUSTRY PATTERN

The matrix from Table 11 shows the pattern for integration enablers in the medical CIMO's analysis. Once again, the numbers show a higher incidence of references regarding the external functions to the organization that collaborate for design for AM.

Further, we will determinate the weight of each one of these enablers while looking in case studies from the medical industry.

	Context	Intervention	Mechanisms	Outcomes
Supplier collaboration	1	2	1	0
Supplier helping with the topology optimization	0	0	0	0
Supplier providing knowledge about AM materials	1	0	0	0
Supplier providing knowledge about AM processes	0	1	1	0
Supplier providing knowledge about AM software	0	2	1	0
Internal capabilities	0	0	0	0
Internal cross-functional integration	0	0	0	0

Table 11 Matrix with integration enablers mentioned in the Medical CIMO's analysis

4.3.2 KEY ENABLERS IN THE MEDICAL INDUSTRY

In the previous section, we discovered the existence of a pattern within medical case studies about what kind of integration and enablers were needed for Design for AM projects. Now, we will explore the incidence of these external enablers in regarding the context, interventions, and outcomes they got. Using the matrix coding tool in NVivo, the following Table 12 was formulated.

Medical	Supplier collaboration	Collaboration for process	Collaboration for material	Collaboration in topology optimization	Collaboration in software	Internal capabilities	Internal cross-functional integration
(AM04_M1)	1	1	0	1	0	0	0
(AM14_M2)	0	0	0	0	0	0	0
(AM15_M3)	1	1	0	0	0	0	0
(AM16_M4)	2	0	0	0	0	0	0
(AM17_M5)	1	0	0	0	0	0	0
(AM18_M6)	0	0	0	0	0	1	0
(AM19_M7)	0	0	0	0	0	0	0
(AM20_M8)	4	2	1	0	0	1	0
(AM21_M9)	5	2	2	0	1	1	0
(AM22_M10)	2	1	0	1	0	0	0
(AM26_M11)	0	0	0	0	0	0	0
(AM30_M12)	0	0	0	0	0	0	0
(AM31_M13)	2	0	0	1	1	0	0
(AM32_M14)	0	0	0	0	0	0	0
(AM33_M15)	2	0	0	0	1	0	0
(AM34_M16)	1	0	0	0	1	0	0
(AM35_M17)	1	0	0	0	1	0	0

Table 12 Medical cases where internal and external integration enablers were mentioned

Under the pattern of the integration enablers in the medical CIMO, Table 12, shows a greater number of mentions to supplier collaborations than to the internal factors. Out of a total of seventeen cases analysed, in eleven of them, at least one type of external enabler was referenced in their report while internal enablers are only mentioned on three occasions.

By investigating the collaboration in knowledge share regarding the AM processes, there is a reference in five cases (AM04_M1, AM15_M3, AM20_M8, AM21_M9, AM22_M10). Most of these case studies share a similar context. The customers seek to find a solution for design and production of patient-specific implants. This is the main reason that led these companies from all the reviewed case studies to seek the help of these services providers, consumers take advantage of personalization through AM has it can be both accurate and reliable.

In the mentioned cases, there are manufacturing constraints considered in the design such as biological functions, high complexity, material quality, and resource effectiveness. The interventions needed and reached outcome reveal a relationship to the type of integration observed. The customers have shown to be inexperienced about additive manufacturing processes (Powder-bed based industrial 3D printing and Direct Metal Laser Sintering (DMLS)), thus, this external collaboration was crucial to fulfilling all the final products preconditions, attaining optimized, innovative, and accurate operative fit implants.

Regarding collaborations for the material choice, there are references in two cases (AM20_M8 and AM21_M9). These are about the design and production of patient-specific complex Orthoses and the development of tracheal splints to treat a congenital breathing condition. Both interventions and mechanisms had to take into consideration material-technical properties, due to the structure complexity (rigidity), material thickness, and need for biomaterials properties. Overall, the collaboration in material knowledge share was important to reach weight reduction, while creating reproducibility in standardized products.

The external collaborations in topology optimizations were mentioned in three cases (AM04_M1, AM22_M10, and AM31_M13). Projects context is the design of an alloplastic facial implant, development of a customized leg prosthesis for a cat, and design and production of a hip implant. The first case comprises an improvement of an existing implant functional design of facial asymmetry that leads to functional problems and aesthetic issues. In all of them, it was required supplier expertise's in design in order to create complex, accurate operative fit, customized implants.

In the medical industry, there's substantial evidence of the importance that a supplier collaboration in software can have in the final outcomes. This is mentioned in five cases (AM21_M9, AM31_M13, AM33_M15, AM34_M16, and AM35_M17). In the context of high personalized implants, the use of service provider software had a tremendous impact on the achieved precision and customization of some of these cases. By giving access to software patches, that enable the customer to change the range of parameters of the machines or using software that creates a 3D reconstruction from MRI imaging, allowed the projects successful outcomes.

Internal capabilities are mentioned in the cases AM18_M6, AM20_M8, and AM21_M9. For the development of patient-specific components context, this internal integration enabler shows a substantial relevance when the expected outcomes are lead time reduction. When employing their own 3D scanners, the design process is shorter.

4.4 CROSS-INDUSTRY ANALYSIS

To better understand the differences and similarities of these two industries when integrating for design for AM, the results of the analysis of the cases were placed side by side. The following Table 13, compares the occurrence of both external and internal functions that collaborate for design for AM in the Aerospace and Medical cases.

Functions that collaborate for design for AM	Aerospace	Medical
External		
Supplier collaboration	21	22
Supplier helping with the topology optimization	8	2
Supplier providing knowledge about AM materials	0	3
Supplier providing knowledge about AM processes	8	7
Supplier providing knowledge about AM software	1	5
Internal		
Internal capabilities	2	3
Internal cross-functional integration	3	0

Table 13 Functions that collaborate for design for AM

Primarily, it can be inferred that under the functions that collaborate for the integration of Design for AM there is a significant difference between external and internal enablers. Not only have a smaller number of internal indicators been identified, but there is also a lower incidence of these in the case studies. Leading to the conclusion of the greater importance of external collaborations in these industrial sectors. However, it should be noted that the internal enablers should also be taken into account when integrating design for AM in a supply chain.

Focusing on the external enablers, the table shows a very similar number of references to supplier collaboration in the Aerospace and Medical fields. Verifying the pattern of the equal impact of these factors.

For the Aerospace industry, the supplier providing knowledge concerning the AM technology and the help with the topology optimization present as the greater evidence for success. While in the Medical Industry, the supplier software share presents as a key role in the design and production of customized implants. Moreover, this comparison reveals a less significance of topology optimization for medical projects and at the same time, references the collaboration in knowledge regarding AM materials.

5 DISCUSSION

The discussion is reflecting on the key elements of the thesis and provides perspective on how the findings are operationalized in connection to the research questions. The discussion further elaborates on how the project contributes to the existing knowledge depository. The limitations of the findings are discussed by embracing the advantages and disadvantages of the study. In conjunction with the limitations, the discussion is providing suggestions for future research, in terms of logical next actions.

The elements of the discussion are presented throughout the four sections; practical implications, theoretical implications, study limitations, and future research (Prætorius 2018).

5.1 PRACTICAL IMPLICATIONS

The findings from this study analysis chapter 4 ANALYSIS, consist of the identification of the key enablers for DfAM integration in the aerospace and medical industries. The major practical implication of this enablers is that it delivers the necessary insight, for both customers and service providers, on what to change in their business strategy.

In the Aerospace industry, the identified enablers for successful collaborations were, amongst all, the help provided by the supplier with topology optimization and the shared knowledge regarding additive manufacturing technologies. Knowing that it can be proposed for the customer's companies to invest in this new production approach. A proposal is the creation of teams of experts in AM design and the involved processes. This would allow exploiting all the benefits of optimized design, instead of adapting for AM, and consequently, result in lead time and cost reductions.

For the Medical Industry, the main enablers are the collaborations regarding knowledge in AM processes and materials, as well as sharing specialized medical software. Therefore, the proposition for the supplier is an investment in teams of experts in the medical industry that can give constant support in the different phases of the production of the component and develop provide their medical software. For customers, as their mindset is changing, they should integrate this technology in their future treatments as it is believed that it's going to be standard of care in the future. Reinforcing partnerships between medical institutions, universities, investors, and suppliers are quite beneficial.

5.2 THEORETICAL IMPLICATIONS

This project contributes to the literature gap described in section 2.3 LITERATURE GAP by presenting a multiple case study analysis on design for AM projects. Although this project is industries specific, the approach can be applied to many other industries. Following a CIMO-logic framework will help to identify internal and external integration enablers for a particular area of study. The findings go in agreement with the literature that states, the structure becoming flat due to the simplicity of processes, reduces the complexity of management and increases the flexibility as well as the resilience of SC operation.

This project highlights the value of the deductive approach when researching the key enablers in successful collaborations for design and its impact on internal and external integration for DfAM.

5.3 STUDY LIMITATIONS

This section is presented in order to highlight some of the limitations of the project and the previous impact of these limitations on the findings and conclusion of the report.

First, it must be noted that the thesis is limited to the study of two specific industries, aerospace and medical. It was initially discovered a lack of academic research on this topic. The choice to focus on only these areas was primarily due to the fact that a similar study was being carried out simultaneously by the supervisor of this thesis, allowing me to highlight the enablers and the specific characteristics of the collaborations in these fields and at the same time, having two industries that allow a cross-industry analysis and reveal their similarities or differences. Also, while studying the medical industry, a decision was made to exclude all dental case studies since the specific study of these cases would already be taking place at the time this project was suggested and accepted.

For the literature review, it was not possible to do an extra round of the process and phases, as well as more extensive research on the topic, due to time limitation. However, this will be recommended further in the discussion section for future research, encouraging the study of more cases and industries.

More, this study only focusses on finished products and for that reason during the formulation of the search strings identified keywords and synonyms for prototyping were made to be further excluded from the search.

The project has met critical limitations during data collection. Initially, this thesis aimed to perform an integrated approach using both primary and secondary data. As primary data, it was planned to conduct several interviews with AM service providers and to customers from the case studies. However, due to the unexpected event of the COVID-19 global pandemic, companies became unreachable and thus it was impossible to collect primary data. This not only would improve the value of the collected data by reducing the lack of information from certain cases, as well as would create a stronger link between the qualitative data from case studies and the interviews.

5.4 FUTURE RESEARCH

In terms of future research, for the next step, it is suggested to expand research to other industries. As the focus went on the enablers for Design for AM in the Aerospace and Medical industries, the findings and conclusions from this study can't be something applicable to all industries without scrutiny. The components from these fields have usually a great design complexity, and their material needs to fulfill many requirements for the final product to be certified. All these standards and regulations from these fields may many times act as a barrier for integration, whereas this constraint might be non-existent in other industries. For that reason, widening the areas of study will allow a deeper knowledge of supply chain integration for design for AM.

It would also be beneficial for future research to investigate the correlation between internal and external enablers. Although in this study it has been shown that there is a greater impact of external functions in design for AM integration, the study leaves open the possible effects that internal changes may have on supply chain integration.

Moreover, with the strong interest growth in additive manufacturing, many companies are starting to change their mindset and slowly wanting to adapt and integrate this technology into their production. Consequently, many types of research will turn their focus on integration for Design for AM. By the time this study was conducted, a literature gap regarding this topic was found but since then things might have changed, therefore its recommended to do another literature review that can fill this gap.

Lastly, given the constraints faced by this study, it is recommended to conduct interviews with both 3D printing service providers and customers. This will give a stronger insight into the different points of view, what does the customer consider as key enablers when collaborating in design for AM projects.

6 CONCLUSION

This thesis proposes to study how different functions internal and external to the organization collaborate for design for AM and identify key enablers in successful collaborations for design in aerospace and medical. Through this project, companies and suppliers can obtain a better understanding of the strategy needed when considering implementing AM in their supply chain.

From the analysis, it can be inferred that there is a significant difference between external and internal enablers under the functions that collaborate for the integration of DfAM. External functions such as collaborations between supplier and customer revealed to be the main drivers for the success of AM projects.

For the Aerospace industry, the knowledge provided by the supplier concerning the AM technology and the help with the topology optimization, present as the greater evidence for this success. While in the Medical Industry, the supplier knowledge in AM software is treated as a key role in the design and production of customized implants, along with the collaboration in knowledge regarding AM materials.

In conclusion, the aerospace and medical industries have characteristics with enormous potential for DfAM integration. The manufacturing constraints typical from these industries can be easily overcome through design, and, as the technology evolves at great speed, it is a matter of time until we see more cases of successful integration for design for AM.

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