THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

AFFORDABLE IDENTIFICATION AND MODELLING OF UNCERTAIN ENGINEERING SPECIFICATIONS WHEN INTRODUCING NEW TECHNOLOGIES IN SPACE APPLICATIONS

OLIVIA BORGUE

CHALMERS

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
GOTHENBURG, SWEDEN 2021

Affordable identification and modelling of uncertain design specifications when introducing new technologies in space applications

OLIVIA BORGUE
ISBN 978-91-7905-549-3

Doctoral thesis at Chalmers University of Technology
Serial number 5016
ISSN 0346-718X

Systems Engineering Design Group
Department of Industrial and Materials Science
Chalmers University of Technology

Published and distributed by:
Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Telephone: +46 (0)31-772 1000
URL: www.chalmers.se

Printed in Sweden by:
Chalmers Reproservice
Gothenburg, Sweden, 2021

ABSTRACT

When introducing new technologies in space products, both the uncertainties regarding technology feasibility and the way in which the technology affects the product development process hinder the early establishment of appropriate engineering specifications. Failing to establish product specifications during conceptual stages leads to problems discovered during later phases of the product development process, when design and process changes are the most expensive.

This thesis proposes a digital holistic design platform and a method of constraints replacement for a cost- and time-efficient identification of specification uncertainties when designing space products with new technologies. The digital platform and methods have been developed and tested through industrial case studies featuring the introduction of new technologies for on-orbit applications. Most of these studies were performed in the context of, but are not limited to, the introduction of additive manufacturing.

The platform and proposed constraints replacement method are based on function modeling strategies (for modeling product architecture and requirements during conceptual design phases), coupled with activity modeling strategies (for modeling the impact of product architecture on product development schedules and costs). The platform and method enable the identification and assessment of unknown uncertainties, thereby reducing the likelihood of expensive redesign processes during later development phases.

Moreover, they enable the inclusion of multidisciplinary design trade-offs during conceptual stages and encourage the establishment of a culture of uncertainty seeking and effective data documentation and transfer.

Keywords: Technology introduction, model-based systems engineering, space components, engineering specifications, uncertainties identification.

ACKNOWLEDGEMENTS

I would like to extend my gratitude to my supervisors Prof. Ola Isaksson and Assoc. Prof. Massimo Panarotto, for their amazing supervision and patience, and for giving me this opportunity. I am also grateful to all my colleagues and co-authors, their professionalism, the endless discussions and reflections, and their experience and knowledge.

This research would have not been possible without the fantastic support from our partners from projects RIQAM, CHEOPS, IDAG, DIDAM and DigiQUAM. I am also grateful to all the organizations that supported our projects: Rymdstyrelsen, Vinnova, EIT Manufacturing, and the European Union's Horizon 2020 research and innovation program.

Two months of my PhD were spent in Italy at SITAEL SpA. for the project CHEOPS. I am endlessly thankful to the company, for giving me this opportunity, and to all the amazing new friends I made there.

This work would not have been possible without the unconditional support and encouragement from my colleagues, friends, and family through these exciting and rewarding four years. Thank you!

Olivia Borgue,
Gothenburg, September 2021

APPENDED PUBLICATIONS

Article A

Borgue O., Panarotto M., and Isaksson O. (2018). Impact on design when introducing additive manufacturing in space applications. In: Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia, pp. 997-1008. https://doi.org/10.21278/idc.2018.0412.

Workload distribution: Borgue acted as main author, and performed the literature studies and analyzed its results, which enabled the results and conclusions presented in this article. Moreover, Borgue actively participated on the empirical studies, their documentation and performed most of the writing activities.

Article B

Dordlofva C., **Borgue O.**, Panarotto M., and Isaksson O. (2019). Drivers and Guidelines in Design for Qualification using Additive Manufacturing in Space Applications. In: International conference of engineering design (ICED) 2019.

Workload distribution: Borgue participated on the development of the interviews, their realization and analysis, as well as elaborating the presented results and conclusions. Moreover, participated in the writing process.

Article C

Borgue O., Müller J., Leicht A., Panarotto M., and Isaksson O. (2019). Constraint replacement-based design for additive manufacturing of satellite components: Ensuring design manufacturability through tailored test artefacts. Aerospace, 6(11), 124.

Workload distribution: Borgue participated on the development of the methodology and led article writing. Moreover, has participated on the empirical studies and the development of the models and their validation, and is responsible for the design of the satellite component.

Article D

Borgue O., Paissoni C., Panarotto M., Isaksson O., Andreussi T., and Viola, N. (2021). Design for test and qualification through activity-based modelling in product architecture design. Journal of Engineering Design, 1-25. doi:10.1080/09544828.2021.1950656

Workload distribution: Borgue developed the methodology and led the article writing. Moreover, has participated on the empirical studies and the development of the models and their validation.

Article E

Borgue O., Panarotto M., and Isaksson O. (2020). Fuzzy model-based design for testing and qualification of additive manufacturing. Under review for Design Science.

Workload distribution: Borgue developed the methodology and participated in the article writing. Moreover, has participated on the empirical studies and the development of the models and their validation.

Article F

Borgue O., Panarotto M., and Isaksson O. (2021). Reducing design uncertainty through model-based collaborative design methods when introducing new technologies: A Solomon four-groups design study. Under review for SN Applied Sciences.

Workload distribution: Borgue developed the methodology, and the data collection workshops. Moreover, was responsible for the data analysis process and article writing.

ADDITIONAL PUBLICATIONS

The following publications are related to the research presented in this thesis, but do not constitute the core findings.

1- **Borgue O.**, Stavridis J., Vanucci T., Stavropoulos P., Bikas H., Di Falco R. and Nyborg L.(2021). Model-based design of AM components to enable decentralized digital manufacturing systems. ICED2021.
2- **Borgue O.**, Valjak F., Panarotto M., Isaksson O. (2020). Supporting additive manufacturing technology development through constraint modelling in early conceptual design: A satellite propulsion case study. In: Proceedings of the DESIGN 2020 16th International Design Conference, Cavtet, Croatia.
3- Panarotto M., **Borgue O.**, and Isaksson O. (2020). Modelling Flexibility and Qualification Ability to Assess Electric Propulsion Architectures for Satellite Megaconstellations. Aerospace, 7(12): pp. 176.
4- Müller J.R., **Borgue O.**, Panarotto M., and Isaksson O. (2020). Mapping the design space in function and geometry models supporting redesign for additive manufacturing. Journal of Design Research, 18(1-2): pp. 37-56.
5- Gonzalez Castro S., Panarotto M., **Borgue O.**, and Isaksson O. (2020). Analysing increase of functionality and complexity in integrated product architectures. DS 101: Proceedings of NordDesign 2020, Lyngby, Denmark, 12th-14th August 2020, pp. 1-12.
6- Martinsson J., **Borgue O.**, Panarotto M., and Isaksson O. (2020). Automatic geometry alteration when designing for metal additive manufacturing. DS 101: Proceedings of NordDesign 2020, Lyngby, Denmark, 12th-14th August 2020: pp. 1-12.
7- Isaksson, O., Eckert C., **Borgue O.**, Hallstedt S.I., Makoto Hein A., Gericke K., Panarotto M., Yoram Reich Y., and Anna B. Öhrwall Rönnbäck A.B. (2019). Perspectives on innovation: The role of engineering design. In Proceedings of the Design Society: International Conference on Engineering Design, vol. 1(1): pp. 1235-1244. Cambridge University Press, 2019.
8- **Borgue O.**, Müller J.R., Panarotto M., and Isaksson O. (2019) Constraints replacement-based design for Additive Manufacturing of satellite components. Function modelling and constraints replacement for additive manufacturing in satellite component design. In: Proceedings of NordDesign 2018.
9- **Borgue O.**, Panarotto M., and Isaksson O. (2019). Modular product design for additive manufacturing of satellite components: Maximising product value using genetic algorithms. Concurrent Engineering, 27(4): pp. 331-346.

CONTENTS

LIST OF ACRONYMS

AM	-	Additive Manufacturing
C	-	Constraint
CC	-	Configurable Component
CAD	-	Computer-Aided Design
CT	-	Computerized tomography
DD	-	Direct Drive
CHEOPS	-	Consortium for Hall Effect Orbital Propulsion System (Project)
DEBAS	-	Design Exploration and Business Activity Simulator (Project)
DfAM	-	Design for Additive Manufacturing
DIDAM	-	Demonstration of Infrastructure for Digitalization Enabling Industrialization of Additive Manufacturing (Project)
DigiQUAM	-	Digital Platform for Additive Manufacturing (Project)
DRM	-	Design Research Methodology
DS	-	Design Solution
DSM	-	Design Structure Matrix
EF-M	-	Enhanced Functions-Means
EIT	-	European Institute of Innovation and Technology
EPS	-	Electric Propulsion System
ESA	-	European Space Agency
FBS	-	Function-Behavior-State
FM	-	Function Modelling
FR	-	Functional Requirement
IDAG	-	Infrastructure for Digitalization Enabling Industrialization of Additive Manufacturing (Project)
KK	-	Known Known
KU	-	Known Unknown
LCC	-	Life Cycle Cost
LPFB	-	Laser Powder-Bed Fusion
NASA	-	National Aeronautics and Space Administration
PD	-	Product Development
PDP	-	Product Development Process
PERT	-	Program Evaluation and Review Technique
PGS	-	Power Generation System
PPU	-	Power Processing Unit
RIQAM	-	Radical Innovation and Qualification for Additive Manufacturing (Project)
RQ	-	Research Question
SED	-	Systems Engineering Design
SV	-	Surplus Value
UU	-	Unknown Unknown
V&V	-	Verification and Validation
VVT	-	Verification, Validation, and Testing
W#	-	Workshop Number #

1

INTRODUCTION

Products for space applications must be able to withstand extreme environments and meet tough requirements when in operation, as the ability to maintain and repair them is limited. For this reason, these types of products are traditionally costly and produced in small batches (Hobday,1998). They are often designed for minimum weight while being able to withstand the dynamic conditions of launching and environmental requirements regarding radiation and thermal gradients (Öhrwall Rönnbäck, and Isaksson (2018).

These requirements have shaped the space industry to be risk averse with low production volumes and long development times, where the main actors are governmental and defense agencies such as NASA, the European Space Agency (ESA), and Roscosmos (Hiriart and Saleh, 2010). The launch vehicle Ariane 5, for instance, had its first series of test flights in 1996 and was in development until 2014. Launches with Ariane 5 rockets were performed from 1997 and are still performed nowadays with a frequency of seven launches per year (ESA, 2019). Their development and launch cost per unit is estimated at 150 to 170 million euros (Selding, 2015).

However, as the industry has evolved (Whitney, 2000), multiple international groups have started competing for commercial markets, fostering the creation of private companies and start-ups in the space sector. Some of the newly created companies are known as "NewSpace" companies and are primarily funded by private capital, with a clear objective of increasing production numbers and lowering costs, thus challenging the traditional methods of space exploration, which are considered too expensive, time consuming, and conservative (Prasad, 2017; Martin 2014). The US-based NewSpace company SpaceX, for instance, began the process to launch into orbit a satellite constellation with approximately 12,000 low-cost satellites. Counterparts, such as the UK-based OneWeb, are planning to deploy similar systems (McDowell, 2020).

In the next 10 years, around 10,000 NewSpace enterprises are expected to be started (Henry, 2016). This change in mentality leads to cost and lead time reductions becoming important driving forces for space manufacturers. For example, the launch vehicle Ariane 6, which was planned to be operational in 2020, was developed under the expectation of a major cost reduction (40%–50%), compared to its predecessor Ariane 5, to compete against the low cost of SpaceX launchers (Shalal, 2019).

This cost reduction was possible through innovative design changes and technical and technological innovation (Cour des Comptes, 2019).

In this context, the introduction of new technologies is attractive for space manufacturing companies due to the increased market competition to target new product functionalities or lower production costs and time, ensuring present and future company permanence in the market and fostering company capabilities.

During the conceptual stages of a product development process (PDP), needs and requirements are identified, refined, and compiled into requirements specifications (Haskins et al, 2015). In the systems engineering (SE) framework, requirements (e.g., "The component shall connect with the pressure vessel in the fluid management system") are translated into engineering specifications from which the product is then designed. Engineering specifications are measurable criteria that the product must fulfill to satisfy the established requirements (Haik et al., 2015) (e.g., "Interface internal diameter [mm]").

When introducing new technologies, engineering specifications are difficult to establish, as previous technical knowledge might have lost its relevance and applicability (Barenbach et al., 2009).

On the one hand, a lack of knowledge and, consequently, an incorrect engineering specification definition in early PDP stages can lead to wasteful redesign loops encountered during later PDP stages (Haik et al., 2015; Dordlofva, 2020).

However, test campaigns for data gathering can be long and resource intensive (Brice, 2011; O´Brien, 2018; Dordlofva, 2020). For example, data-gathering activities for introducing new materials or manufacturing technologies often require millions of dollars and five to 15 years to be completed (Brice, 2011).

Due to this lack of knowledge, development projects with new technologies might have either test phases that are too long and expensive or redesign loops that disrupt the PDP schedule, hence introducing delays and additional costs. New technologies could consequently be abandoned or not used to their full potential (Thompson et al., 2016).

The ability to gather data to establish engineering specifications in a time- and cost-efficient manner during conceptual stages is generally imperative to foster the introduction of new technologies.

1.1. Research positioning, scope, and limitations

The presented work was carried out at the Systems Engineering Design research group, which is part of the division of Product Development at the Department of Industrial and Materials Science at Chalmers University of Technology. The research group aims to understand and address the needs of product-developing organizations through the development and improvement of design- and technology-integration theories, methods, and tools.

In this context, the research presented in this thesis is concerned with the development of model-based methods for the design of complex space products with new technologies. In this thesis, "space products/components" refer to mechanical or electric components for on-orbit space applications, such as the components of a propulsion system for satellite applications. Moreover, the characterization of "complex" refers mainly to the high number of customized components and the amount of knowledge and skills required for their development and production.

This research is based in a context where the new technologies that intend to be introduced are already aligned with company objectives and have already been selected for implementation. The thesis is not concerned with the selection of the most appropriate technology/technologies for a certain application, but rather with the development of design support adapted to work with those technologies.

In this line, when "new technologies" are mentioned in this thesis, they are mentioned to reference technologies whose implementation is novel in the context of a specific company.

Throughout this thesis, "data," "information," and "knowledge" are recurrent concepts. Although the literature defines them in numerous ways, the following definitions, elicited from the work by (Chen et al., 2008), are adopted in this work:

- Data: sets of individual, out-of-context facts.
- Information: sets of contextualized relevant data at a point or in a period of time.
- Knowledge: acquaintance or understanding of information.

1.2. The product development and product design context

This thesis is positioned in the concept stage of product development (PD), as defined by SE literature (Haskins et al., 2015). The SE model, as proposed by Haskins et al. (2015), is presented in Figure 1.1.

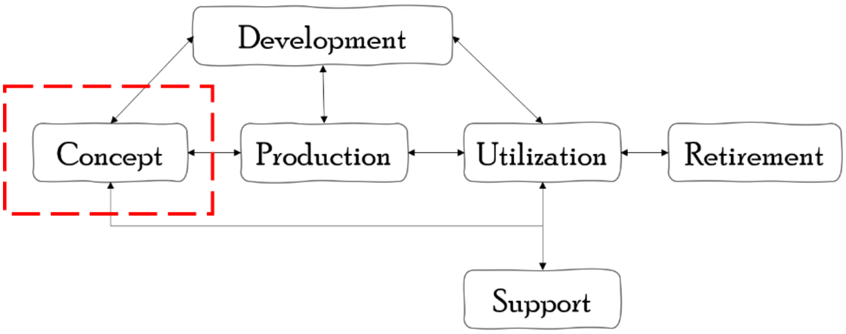


Figure 1.1. Thesis positioned in the product development process (PDP) proposed by the INCOSE's Systems Engineering (SE) Handbook, adapted from Haskins et al. (2015).

According to the SE Handbook by INCOSE (Haskins et al., 2015), in the concept stage, a stakeholders' needs analysis, exploratory research, and technology studies are performed (Figure 1.1). Requirements are specified for subsequently developing and assessing product concepts through early performance, cost, and schedule projections. This stage includes a preliminary architecture definition as well as the planning of verification and validation (V&V) activities.

Design is at the core of SE (Buede and Miller, 2016; Haskins et al., 2015). However, authors such as Shafaat and Kenley (2015) and Buede and Miller (2016) state that when SE models, such as the Vee model, are applied, the iterative and explorative nature of the design process is generally disregarded.

Disregarding design iterations and design space exploration can have consequences with respect to the designers´ ability to recognize and deal with system complexity (Shafaat and Kenley, 2015).

Engineering design (ED) is the discipline that focuses on design space exploration and iteration during PD (Suh, 1990; Chakrabarti and Blessing, 2014).

In terms of ED-centric literature, this thesis is concerned with PD activities related to the design of product architectures and product design concepts. For example, Eppinger and Ulrich (2015) identify these early stages as the system-level design phase (Figure 1.2.) where the product architecture is generated, product subsystems and interfaces are defined, and preliminary components' designs are established.

Design strategies applied in conceptual phases of the PDP provide tools for dealing with early changes in requirements and design specifications. Moreover, as knowledge regarding design for new technologies is limited, its early modeling and enabled simulation capabilities can facilitate its efficient management and implementation (Eppinger and Ulrich, 2015).

For understanding, analyzing, and improving the PDP a vast number of PDP models are proposed in literature; a comprehensive review of these models can be found in the work by authors such as Smith and Morrow (1999), Haskins et al. (2015), and Wynn et al. (2018). However, the point is that, in this thesis, the focus is on early conceptual design phases, not on the phases where a clear, embodied concept is readily available.

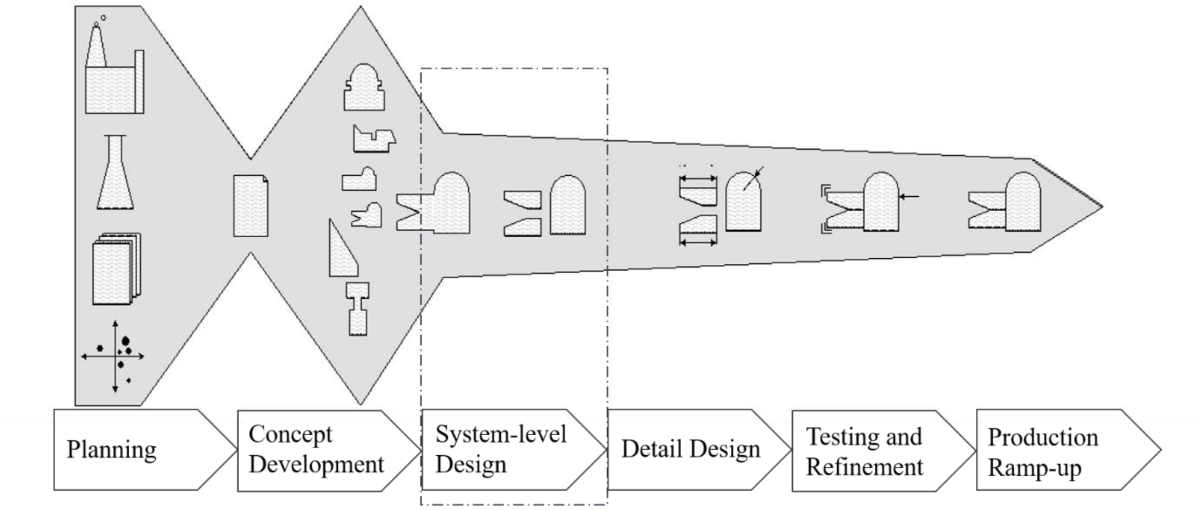


Figure 1.2. Thesis positioned according to the PDP proposed by Eppinger and Ulrich (2015).

Despite the proficiency of the ED discipline in design exploration and ideation, the SE community often criticizes ED for its difficulty to be applied in an industrial setting and its disregard for verification, validation, and testing (VVT) phases (Buede and Miller, 2016). Other differences between SE and ED are presented in Table 1.1.

Table 1.1. Differences between systems engineering (SE) and engineering design (ED)

Systems Engineering	Engineering Design	Reference
Rich in concepts and practices to handle system complexity	Lack of conceptual richness and strategies to handle system complexity	(Shafaat and Kenley, 2015)
Product/system centered: disregard for extensive idea generation phases	Human centered: ideation, design fixation avoidance	Brown (2009), Greene et al.(2017)
Well-known terminology in industry	Mainly known and implemented in academia	Cross (2001), Greene et al. (2017)
Mostly based on industrial definitions and established practices	Strong theoretical basis	Cross (2001); Greene et al. (2017)
Design space exploration is often disregarded	Emphasis on design space exploration	Pahl et al. (2007), Buede and Miller (2016)
Design iterations are often disregarded when planning and budgeting	Design iterations are expected and encouraged	Pahl et al. (2007), Shafaat and Kenley (2015)
Focuses on requirements validation	Requirements' validation is often disregarded	Buede and Miller (2016)
Focuses on modeling system specifications, design, and	Focuses on modeling relations between objects (functions, design	Haskins et al. (2015), Hatchuel

verification and validation phases, with the purpose of design analysis and optimization	solutions, activities, etc.) to understand their interaction and explore the design space	and Weil (2009), Gero (1990), Gero and Kannengiesser (2007)

When the disciplines of SE and ED are combined, the resulting discipline is referred to as systems engineering design (SED), which focuses on the ED of products, while taking a systems (holistic) perspective (Isaksson et al., 2017). The studies conducted in this thesis pertain to the SED domain.

1.3. Research questions

New technologies are attractive for space companies to, for instance, target new product functionalities or lower production costs and time. However, the lack of knowledge regarding a new technology hinders the early establishment of engineering specifications to satisfy design requirements.
PDP with new technologies must consequently incur exhaustive test phases to gather the required data or undergo expensive redesign loops due to problems arising in later phases of the PDP. Both consequences can render the PDP too expensive and lengthy. Moreover, efforts to introduce the new technology might be abandoned.
In this context, this thesis proposes three research questions to be addressed:

RQ1: *What are the main knowledge gaps during conceptual stages that hinder the establishment of engineering specifications for the introduction of new technologies in the space industry?*

RQ2*: What factors hinder data gathering for the establishment of specification requirements related to technology capabilities and their impact on the V&V schedule?*

RQ3*: How can uncertain engineering specifications be identified and modeled in a cost- and time-efficient way during the concept stage?*

1.4. Thesis structure

The contents of this thesis are structured as follows. Chapter 1 presents the main problem that motivated this research, along with the background, the context, and the research questions that this thesis aims to address. In Chapter 2, the frame of reference is introduced, and in Chapter 3, the research methodology employed for conducting this research is presented. Thereafter, in Chapter 4, the five appended articles, which are the backbone of this thesis, are introduced together with their key results and findings. Those findings are then discussed and used to answer the research questions in Chapter 5. The thesis results are subsequently discussed in Chapter 6, and their validation is addressed in Chapter 7. Finally, concluding remarks are presented in Chapter 8.

2

FRAME OF REFERENCE

2.1. The evolution of the space industry

According to authors such as Hobday (1998) or Haskins et al. (2015), space products can be classified as complex products, as they have a high cost and value and are engineering-intensive, with emphasis on design, project management, and systems integration. Moreover, space products must withstand extreme launch and operation conditions and then operate in an autonomous and reliable way for periods that, in the case of satellite applications, can be extended to more than 15 years (Öhrwall Rönnbäck and Isaksson, 2018).

These requirements have shaped the space industry to be conservative and risk averse with low production volumes and long development times, and the main actors have traditionally been governmental and defense agencies such as NASA, the ESA, and Roscosmos (Hiriart and Saleh, 2010). The traditional space industry pursues goals set by governments, based on political and social forces and funding sources (Chechile, 2021).

During the early years of the space industry, technologies were developed in and for space applications and transmitted to other industries. However, nowadays, technologies are spinning into the space industry from other industries, helping to reduce the costs and increase the performance of many space applications, such as telecommunications, Earth observation, and space exploration (Lal, 2016).

The introduction of new technologies that enable performance increases and cost decreases are key drivers for what is called the “democratization of space,” enabling the advent of companies primarily funded by private capital with a clear objective of increasing production numbers and lowering costs, thus challenging the traditional methods of space exploration, which are considered too expensive and time consuming (Martin 2014; Prasad, 2017; Chechile, 2021).

These private companies are usually termed “NewSpace” companies; some examples are SpaceX, One Web, Vector, Virgin Galactic, and Planet Labs (Martin, 2014; Prasad, 2017; Lal, 2016).

NewSpace initiatives pursue non-governmental goals, responding mostly to market tendencies toward cost and development time reductions. These initiatives usually engage in risk-taking endeavors based on private funding, experimenting with disruptive innovations, rapid development cycles, and large production numbers (Chechile, 2021).

The US-based NewSpace company SpaceX, for instance, started the process to launch into orbit a satellite constellation with approximately 12,000 low-cost satellites. Other companies, such as the UK-based OneWeb, are also planning to deploy similar systems (McDowell, 2020).

In the next 10 years, around 10,000 NewSpace companies are expected to be started (Henry, 2016), and the space economy is expected to move toward civilianization and internationalization (Lal, 2016). The democratization of space is leading the space industry into an era of increased market competition and mass customization with a growing need for cost and time-to-market reduction strategies.

This change in mentality means that cost and lead-time reductions are becoming important driving forces for space manufacturers (Cour des Comptes, 2019).

The launch vehicle Ariane 6, for instance, which was planned to be operational in 2020, was developed with the expectation of a major cost reduction (40%–50%), compared to its predecessor Ariane 5, to compete against the low cost of SpaceX launchers (Shalal, 2019).

To remain relevant in a competitive market, disruptive technologies are attractive for space companies to target new product functionalities or lower production costs, ensuring company permanence in the market and fostering new company capabilities (Loch and Kavadias, 2008; European commission, 2019).

2.2. Technology introduction in space products

The introduction of new technologies is attractive for space companies. However, technology development is expensive and takes a long time, especially the space hardware development cycle, which is considerably longer than in general tech (European commission, 2019).

There is a need to reduce the costs and times of technology introduction processes in the space industry. However, two major hinderances exist: a lack of information about technology capabilities (Veritas, 2001; Brice, 2011; Dordlofva, 2020; Echsel et al. 2020) and a lack of information about the impact that a new technology has on a PDP, especially on V&V activities (Lord et al., 2018, European commission, 2019; Dordlofva, 2020), which can constitute 55% of a technology's life cycle cost (LCC) (Engel and Barad, 2003; Tahera et al., 2019). A lack of knowledge and, consequently, poorly defined engineering specifications in early PDP stages can lead to wasteful redesign loops encountered during later PDP stages.

In their study about additive-manufactured satellite sandwich structures, Echsel et al. (2020) manufactured sandwich structures that failed their V&V tests due to previously unknown AM material behaviors that caused water vapor to be trapped in the structure during the manufacturing process. The authors proposed further investigation and adjustments of the manufacturing process and a reestablishment of design specifications.

Furthermore, in their analysis of the design of a rocket engine turbine, Dordlofva (2020) pointed out the need to include, during conceptual stages, requirements and engineering specifications related to component V&V activities. For instance, if one considers the available inspection methods and established engineering specifications for a design that can be successfully inspected, failing to perform V&V activities can result in expensive redesign loops.

In this context, three design and development alternatives are predominantly found in the literature on technology introduction (Brice, 2011; O´Brien, 2018):

(1) Design an innovative product, and increase confidence in its quality and performance through extensive data-generation campaigns with long and expensive test activities.

(2) Create a conservative design with a limited amount of testing, but miss more radical performance improvement opportunities (Thompson et al., 2016).

(3) Produce an innovative design, but perform little testing and data-gathering activities.

On the one hand, the problem with alternatives (2) and (3), which are not test intensive, is that technologies do not always perform as expected (Echsel et al. 2020): Not addressing uncertainties leads to redesign loops.
On the other hand, test campaigns for data gathering—alternative (1)—can be long and resource intensive (Brice, 2011; O´Brien, 2018; Dordlofva, 2020). For example, data-gathering activities for introducing new materials or manufacturing technologies often require millions of dollars and five to 15 years to be completed (Brice, 2011).
Due to this lack of knowledge, development projects with new technologies might have either test phases that are too long and expensive or redesign loops that disrupt the PDP schedule, thereby introducing delays and additional costs. New technologies could consequently be abandoned or not used to their full potential (Thompson et al., 2016).
In this context, to foster the introduction of new technologies, it is imperative to gather data to define engineering specifications related to technology capabilities and VVT activities in an affordable (time- and cost-efficient) manner during conceptual stages.

2.3. Verification and validation activities in the space industry

V&V activities are activities performed to demonstrate that a system or a system element fulfills its specified requirements (verification) and its business objectives and stakeholders' requirements in its operational environment (validation). Problems discovered during these stages are expensive to fix (Haskins et al., 2015).
Among the V&V activities, four categories are highlighted (Haskins et al., 2015):

- Acceptance: This activity is conducted prior to a transition process, so the acquirer can decide whether the system provided by a supplier entity is ready to change ownership to the acquirer.
- Certification: This activity is conducted to ensure that the system has been developed and is able to perform its functions in accordance with an appropriate standard.
- Readiness for use: This activity is conducted to ensure that the system is ready and has all the required capabilities to be used.
- Qualification: In the space industry, "qualification" encompasses activities that, as the SE Handbook explains (Haskins et al., 2015), ensure that a product meets its design, quality, and reliability requirements as well as safety and legislative norms (ISO, 2020; Dordlofva, 2020). These objectives are attributed to the end stages of the VVT activities performed in the SE field (Shabi et al., 2017). Moreover, the ISO standard ISO/IEC/IEEE 12207-2:2020(E) draws a parallel between verification activities and qualification (ISO, 2020).

For already-established manufacturing technologies, several qualification standards exist that guide qualification activities. Such is the case of NASA qualification standards for casting NASA-STD-6016 (materials), -5009 (non-destructive tests), -5012 (structures), and -5019 (fracture control) (Biliyard, 2018). According to standards and common practices (NASA, 1970), each qualification test has its own pass or fail criteria, which are determined before the test is performed. In the case of qualification tests to assess a component's response to environmental loads, for instance, a test can be considered to have failed when the presence of fatigue cracks, excessive structural deformation, or instabilities are observed in the component after the test.

The criteria for the evaluation of qualification tests are often derived from extensive failure mode effect and criticality analysis (FMECA) studies (Borgovini et al., 1993), where the criticality of failure modes is identified and its impact is assessed through simulations and testing.

In early design phases, product design requirements and specifications, along with their associated loads (including those related to failure modes and their criticality), are not completely established and are typically evolved and refined as the PDP advances.

Based on experience, early testing activities, and previous projects' data, designers must assess how design choices will impact the qualification processes (Borgovini et al., 1993; Dordlofva and Törlind, 2018). In this context, design development and qualification are performed iteratively during PD; however, design iterations due to failed qualification tests can result in expensive delays on a PD schedule.

Authors such as Pecht (1993), Preussger et al. (2003), Yadav et al. (2006), and Rausand (2015) maintain that to reduce design iterations due to failed qualification tests, the elaboration of qualification requirements and related engineering specifications must be addressed in the early stages of a PDP.

Some qualification approaches implemented in other industries have successfully followed these principles. This is the case in the qualification process presented by NATO AVT-092 (2009) for military aircrafts, aiming at reducing the time and cost of their production and focusing on the early use of analysis and the integration of tools. In a similar vein, other authors, such as Andersen (2006), Grady (2006), and Engel (2010), have proposed guidelines for qualification procedures to be considered early within the PD process.

However, literature that includes an explicit identification and elaboration of engineering specifications related to V&V requirements is still lacking. This lack of a systematic connection between V&V phases and conceptual stages renders it difficult for one to assess how different design parameters affect qualification ability.

When introducing a new technology, the problem related to loosely defined V&V engineering specifications in conceptual phases is aggravated by the designers´ lack of experience with designing and qualifying a product with the new technology. This in turn increases the risk of encountering problems during V&V activities, which would lead to expensive redesign processes.

2.4. Verification and validation activities for new technologies

To decrease uncertainties about the implementation of a new technology, current qualification strategies for technology introduction are based on extensive tests required depending on the technology type, confidence in analyses, and previous documented experience with similar technologies (Veritas, 2001; Murthy et al., 2008; Furtado et al., 2016). Authors such as Engel and Barad (2003) and Tahera et al. (2019) state that the cost of test activities in a regular PD process can be up to 40% or 55% of the cost of the total LCC. These costs can be expected to be higher when introducing new technologies (Furtado et al., 2016).

In their literature review of qualification methods for technology introduction, Rausand (2015) stated that apart from requiring lengthy data-gathering test phases, the most popular qualification methods are not well linked to the PD process. Moreover, those methods do not support process feedback to establish qualification requirements and improve the product design or its development process, which is deemed necessary for introducing new technologies, as experience implementing the technology is rather limited. According to the author, failing to comply with these criteria (among others) increases the likelihood of qualification failures and redesign loops. The author thus proposes a new qualification strategy with well-defined and organized qualification activities, performed in parallel with a PD process and that promotes process feedback to improve a product design according to early qualification criteria and results. However, no explicit procedures or guidelines are proposed for developing qualification-related specifications or for assessing the influence a new design on the qualification phases.

The lack of systematic design for qualification (DfQ) guidelines for conceptual stages hinders the introduction of new technologies in high-risk or critical components in the space industry (Dordlofva, 2020). Additive manufacturing (AM) technologies are a compelling example of this phenomenon. Although there is a growing interest among space manufacturers in introducing AM to reduce weight, cost, and time to market (Meisel et al., 2017; O´Brien, 2018), most examples of AM parts that have been successfully developed and implemented in the space industry are non-critical (Dordlofva, 2020). In a non-critical component, failure can be accepted without fatal consequences, and the margins can be narrowed down and accepted. The lack of critical space components manufactured using AM is mostly due to the qualification of AM still being a challenge (Meisel et al., 2017), as there is a lack of understanding of AM processes (Thomsen et al., 2017) and a lack of standardized approaches to ascertain the quality of AM parts (Shabi et al., 2017). The statistical spread in properties is not acceptable for critical products (Furtado et al., 2016).

The lack of knowledge and the consequent uncertainty regarding AM material properties would require AM-critical components to have longer testing phases and larger design margins (Dordlofva, 2020). However, longer testing phases and more robust design margins might render the benefits of AM (associated with weight, cost, and lead-time reductions) obsolete.

To address the uncertainties regarding new technologies and to be able to establish appropriate design specifications and safety factors when needed, authors such as NRC (2010), Brice (2011), Karlow Herzog (2018), and Mokhtarian et al. (2019) recommend the early implementation of model-based design methods. These methods can reduce the consequences of the uncertainties related to a new technology and implement the little data and experience available about them, to evaluate the influence of design and process parameters on component quality (Haskins et al., 2015).

Moreover, model-based methods can provide information about tests that can be performed early in the development process to enrich current knowledge about the product under development, thereby potentially reducing the need for some later test activities (NRC, 2010; Pasquinelli et al., 2014; Furtado et al, 2016).

In this way, model-based methods could enable a proper assessment of failed items during early phases and the implementation of parameter-specific corrective actions, exploiting test results for the improvement and validation of analysis models and enabling data gathering that would support future design projects (Pasquinelli et al., 2014).

2.5. Model-based methods and uncertainty in conceptual stages

2.5.1. Models in systems engineering

Model-based design frameworks and methods can quantify, manage, and possibly reduce technology uncertainties—examples are the frameworks presented by Blair and Love (2003), Robinson (2011), and Schmollgruber (2018)—through models and estimations using available data. by implementing these strategies, estimations about the new technology can be used for analyzing design trade-offs in conceptual design phases (Pasquinelli et al., 2014; Furtado et al, 2016).

Multidisciplinary model-based strategies and performance simulations are widely used for uncertainty assessment and reduction (Struck and Hensen, 2007; Ogaji et al., 2007; Goldberg et al., 2018) during conceptual stages.
For instance, there have been several model-based tools for modeling PD uncertainties in the SE discipline in the context of aerospace applications. NASA's IDEA (Robinson, 2011) is a collaborative environment for the parametric conceptual modeling of launch vehicles and is based on the object-based adaptive modeling language (AML) framework (TechnoSoft, 2021). This platform integrates aspects such as geometry, aerodynamics, reliability, costs, and structural analysis into a knowledge-based, generative and parametric, unified model for sharing data across disciplines. Its predecessor, the SBAAT (Bair and Love, 2003), is also based on the AML framework and is a design-modeling product for identifying technology needs and prioritizing technology solutions. Moreover, it includes a process-based affordability assessment in the technology development assessment phase of PD. Similar modeling frameworks were proposed by NASA, with their advanced engineering environment (AEE) (Rowel and Korte, 2003); Stephenson et al. (2007); the CREATE-AV team, with their DaVinci tool (Roth et al., 2010); and Smith et al. (2019).
These efforts are based on tightly coupled geometric modeling, with aerodynamic or structural analysis and optimization. However, they lack the focus on a wider range of design parameters and operational scenarios, rendering then rigid in their design exploration (Raju, et al., 2012).

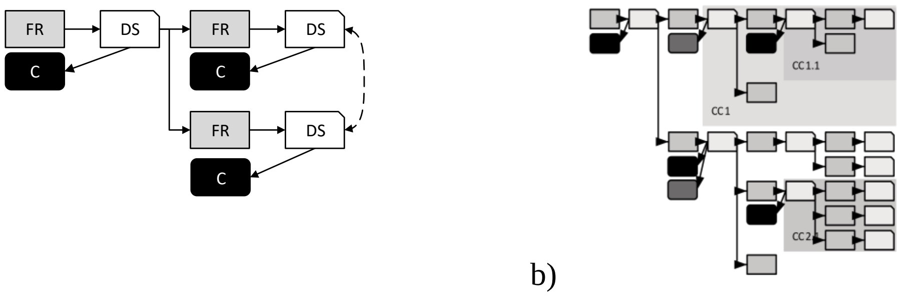
2.5.2. Function modeling in engineering design

ED is a discipline concerned with engineering-related problem solving through ED processes, methods, and tools. The ED process has a strong focus on design exploration and iteration largely based on function modeling (FM) techniques (Suh, 1990; Pahl et al., 2007). Through the inclusion of ED methods in SE frameworks, SED (Isaksson et al., 2017) strives for function analysis and iterative ED efforts in a holistic multidisciplinary framework.
The main advantage of modeling methods is the systematic arrangement and visualization of system information to support designers in making decisions about product architectures and to manage uncertainties and complexity in multi-technology environments (Eisenbart et al., 2012). These techniques have been adopted as a support design method for PDP, as they facilitate product analysis (Raja and Isaksson, 2015), foster collaborative design environments acting as boundary objects (Eisenbart et al., 2015), and facilitate design space exploration (Müller et al., 2020).
Moreover, their flexibility and capability of evolving to adjust to new information and system requirements as well as their level of abstraction (Müller et al., 2020) make them prime candidates for the introduction of new technology and the analysis thereof during conceptual stages.
Multiple FM representations have been developed over the years, such as the one proposed by Gero (1990) and Gero and Kannengiesser (2007), namely, the function-behavior-state (FBS) model for modeling a system with its functional descriptions; the one proposed by Hirtz et al. (2002) for a clear and concise functional basis for mechanical design; or the functions template strategy adopted by Heller and Feldhusen (2013) for creating unambiguous function structures. These representations aim to facilitate the connection between an abstract system concept (system architecture) and the physical design (Eisenbart et al., 2012).
These types of modeling techniques link functional requirements (FRs) with product design features and can incorporate different types of interactions among design features (material, signal, energy, geometry) into the model, thereby providing modeling support to be used across disciplines, as it can represent multidisciplinary requirements utilizing a common language.

In this thesis, a function is defined as "intended behavior" (Vermaas, 2013), although there is no unique definition of the term in the literature. In a function model, the main product function is first identified, and the complete product system is then decomposed into subfunctions that are hierarchically arranged in a function tree (Erden et al., 2008).

The enhanced functions-means (EF-M) is an example of an FM technique. It has been developed and used for over 20 years (Malmqvist, 1997) and is among the more industrially tested FM frameworks (Müller et al., 2020).

In this technique, a hierarchical product structure (Johannesson and Claesson, 2005) is provided that associates FRs with design solutions (DS) to perform those functions, which can be subject to design constraints (C). DSs can be modeled on their interaction with one another via geometry, signals, energy, or material flow. The mentioned modeling elements are illustrated in Figure 1.a. The design rationale that is created through this structure iterates between FRs and DSs. This structure, illustrated in Figure 2.1.b, allows one to identify the impact of constraints and to determine how a change in a function or constraint affects the product structure. Moreover, to enable a segmentation of the product structure, configurable components (CC) are implemented in EF-M as well. CCs, introduced by Claesson (2006), are objects that encapsulate an entire branch (DSs and sub-elements) of an EF-M tree, as depicted in Figure 2.1b.



a) b)

Figure 2.1. Enhanced functions-means (EF-M) modeling: a) modeling elements, based on (Johannesson and Claesson, 2005), and b) levels of EF-M tree based on (Claesson, 2006) and encapsulation through configurable components (CC).

Function models aid in understanding product architectures and can enable the representation of constraints in early phases of the PD process. To deal with the continuous changes in requirements and design assumptions that arise naturally from the implementation of a technology that is still under development (NRC, 2010), the constraint modeling feature of EF-M models is critical.

Moreover, the ability to represent interactions between DSs enables a direct connection with design structure matrixes (DSM). A DSM (Steward, 1981) is a system engineering tool that provides a visual and analytic representation of a system, usually implemented for optimization procedures of design processes (Browning, 2015; Tompkins et al., 2020). A direct connection between a DSM and an FM facilitates the correct identification of interactions among DSs, enabling a correct understanding of the project schedule and cost (Qian et al., 2011). The implementation of DSMs is widespread in the field of engineering and in the design of complex systems for the space industry (Chang et al., 2007; Lee et al., 2010; Qiao and Ryan, 2015).

2.5.3. Activity modeling in the product development process

As discussed in previous sections, design development and test activities are performed iteratively during the whole PDP. Data obtained from test activities can be expensive both in terms of cost and time. Therefore, how and when these data are used is critical, as this can affect the cost and duration of PD activities.

Efforts to model test activities, such as VVT activities, are hence widespread and contribute to the establishment of affordable test phases. In their review of the modeling of test activities, Tahera et al. (2019) indicate that most VVT modeling methods focus on the schedule of a given set of test activities to optimize PD times. Other studies are concerned with choosing the most appropriate test activities considering cost and risk.

Since the cost of test activities can be as much as 55% of the total LCC (Engel and Barad, 2003; Tahera et al., 2019), these activities should be tailored to different product architecture scenarios to reduce costs and schedule times (Wang et al., 2008).

Numerous strategies can be employed to reduce PD costs through the optimization of the development phases, and numerous strategies exist to reduce the cost of the VVT phases (Tahera et al., 2019). However, literature does not provide mechanisms to enhance the conceptual design phases with insights (or requirements) from the test phases. There seems to be an underlying assumption that sufficient upfront information is available about the technologies considered and the product itself, as well as how the associated VVT can be conducted. However, when introducing new technologies, information about product design and the corresponding VVT activities might not be available (Wang et el., 2008).

For introducing new technology in space applications, one must establish a connection between the conceptual phases and the later VVT phases such that insights from the VVT activities can be considered for improving a product's architecture. Similarly, a connection between these two phases would facilitate the assessment of how new design alternatives affect the cost and duration of VVT, thus reducing uncertainties and fostering the development of space products with affordable VVT activities.

3

RESEARCH APPROACH

3.1. Research context

The content presented in this thesis was developed in the context of several research projects:

- Radical Innovation and Qualification for Additive Manufacturing (RIQAM) (08/2017–12/2018), with financial support from Rymdstyrelsen, Swedish National Space Agency (Rymdstyrelsen, 2019). RIQAM, an industrial project, was a collaboration between Chalmers University of Technology, Luleå University of Technology and three major manufacturers of space components in Sweden: GKN Aerospace Engine Systems (GKN, 2019), RUAG Space AB, and OHB Sweden AB (OHB, 2019). The purposes of the project were to demonstrate the potential of AM for space applications and to identify changes in the PD process required to implement AM in space products.
- Consortium for Hall Effect Orbital Propulsion System (CHEOPS) (11/2016–01/2021), founded by the European Union’s Horizon 2020 research and innovation program. CHEOPS was a project with the participation of more than 10 European aerospace companies (such as Thales Alenia Space France/Belgium, Airbus SAS, and Safran) and the University Carlos III of Madrid. This project involved the development of three different innovative hall effect thruster electric propulsion systems (EPSs), each with a different application field and orbit (CHEOPS, 2020).
- Infrastructure for Digitalization Enabling Industrialization of Additive Manufacturing (IDAG) (06/2019–12/2019), with the financial support of Vinnova. The aim of the IDAG project was to identify gaps in complex value chains where digitization solutions for the industrialization of AM were needed (Kunskapsformedlingen, 2019).
- Digital Platform for Additive Manufacturing (DigiQUAM) (01/2020–12/2020), founded by EIT Manufacturing. DigiQUAM was a manufacturing project involving four European partners, namely, Prima, Lortek, RISE, and Chalmers, with the objective of developing an AM software platform (RISE, 2020). DigiQUAM was based on the preliminary studies performed during the IDAG project.
- Demonstration of Infrastructure for Digitalization enabling industrialization of Additive Manufacturing (DIDAM) (02/2020–02/2023), with financial support from Vinnova. DIDAM has the objective of demonstrating and developing the critical parts of a digital infrastructure required to industrialize AM. The partner organizations of this project were Volvo Group, Epiroc AB, Eurostep Group, Uddeholms AB, Brogren Industries AB, and RISE Research Institutes of Sweden.

- Design Exploration and Business Activity Simulator (DEBAS) (04/2021–09/2021), with financial support from Chalmers Innovation Office, under reference V616. The objective of the DEBAS project is the development of a standalone digital application (minimum viable product) composed of two modules. The first module focuses on design exploration as the embodiment of the model platform developed during these PhD studies. The second module contains a surplus value (SV) model for simulating business activity and business cases.

Figure 3.1 presents the main articles on which this thesis is based in the context of the research projects.

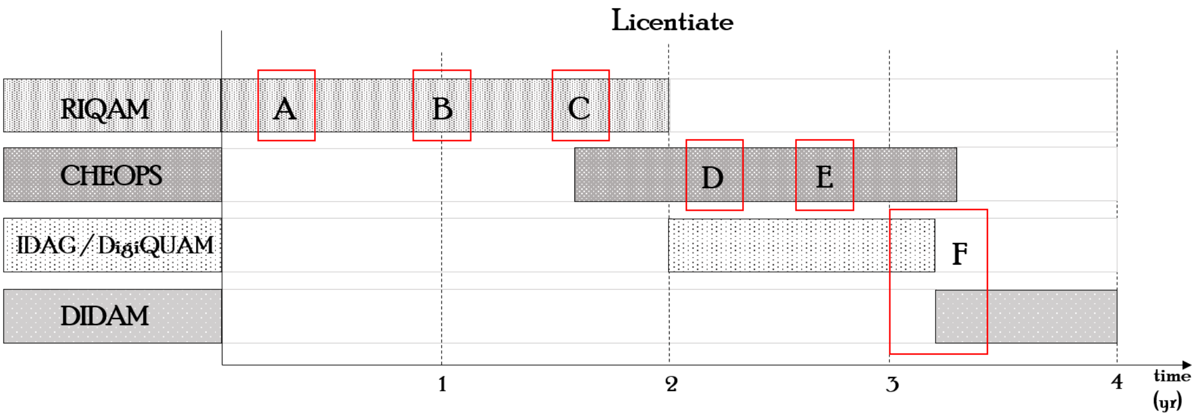


Figure 3.1. Main articles included in this thesis and their positioning according to the research projects.

3.2. Research framework

Research can be defined as a “Systematic and logical study of an issue or problem or phenomenon through a scientific method” (Krishnaswamy and Satyaprasad, 2010). Different research methodologies are chosen to address research gaps and research questions; an appropriate research methodology should enable data collection to answer the research questions.
The different studies that make up this thesis can be organized in a research framework, which is based on the design research methodology (DRM) proposed by Blessing and Chakrabati (2009). The aims of this framework are to create an understanding of certain phenomena and to improve them. The DRM framework is composed of four iterative basic stages, represented in Figure 3.2: 1) research clarification, for identifying and clarifying the research problem; 2) Descriptive Study I, for increasing the understanding of the research problem through empirical studies; 3) a prescriptive study, where methods to address the research problem are developed and applied; and 4) Descriptive Study II, where the impact of the proposed method is evaluated.

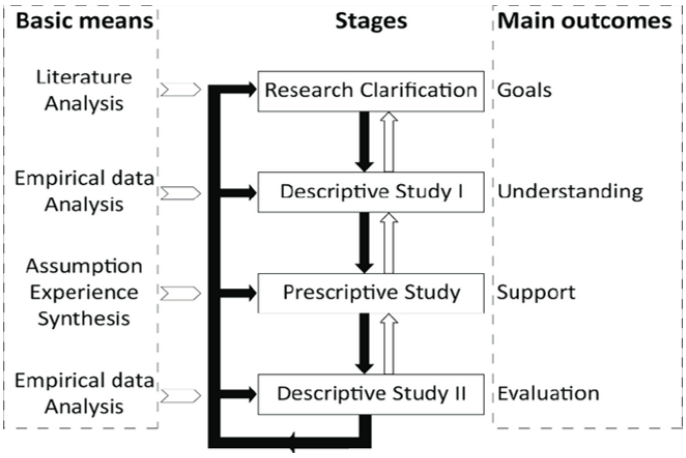


Figure 3.2. Design research methodology (DRM) framework (Blessing and Chakrabarti, 2009).

Each of the six appended articles in this thesis has contributed to different stages of the DRM framework. Their contribution is illustrated in Figure 3.3.

The research conducted for the thesis began with an article entailing a systematic literature mapping around design for additive manufacturing (DfAM) methods and design practices in the space industry (Article A). The aim of this article was to research how a DfAM methodology can support the introduction of AM in space components considering the benefits and limitations of this technology. Thereafter, in the RIQAM project, empirical studies commenced through a series of workshops attended by practitioners from industry, Luleå University, and Chalmers University of Technology. In those workshops, it was possible to directly observe three different space products being redesigned for AM. Articles B and C are based on the empirical results obtained from those workshops. In Article B, the state of the art of V&V procedures in the space industry is analyzed. The conclusions of this study were used to highlight the need to introduce V&V requirements in conceptual stages when designing for a new technology. In Article C, the first part of a model-based method for technology feasibility requirements identification is proposed, and reflections about its application in the context of RIQAM are also presented therein.

In Article D, a modeling method that models V&V activities in relation to early product architecture designs is proposed. The method is applied and discussed in the context of the CHEOPS project. Furthermore, the aim of Article F is to continue the method proposed in Article E linking specific design parameters to the risk of failure during V&V activities. In Article F, the methods proposed in Articles C, D, and E are unified, and their usefulness is assessed through a Solomon four-group study (Sawilowsky et al., 1994) performed in the context of the DIDAM project.

Figure 3.3 illustrates the extent to which the appended articles contribute to the different stages of the DRM framework. The contribution of the different articles is represented by circles of different sizes (a larger circle = a larger contribution).

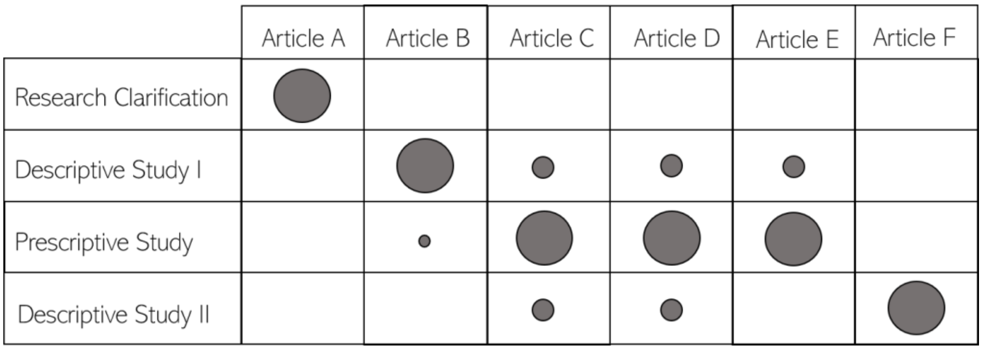


Figure 3.3. Positioning of the thesis articles according to the DRM framework.

3.3. Data collection procedures

The research activities have been performed in the context of the RIQAM, CHEOPS, IDAG, DigiQUAM, and DIDAM projects. Moreover, each article was developed in close collaboration with industry practitioners. The performed data collection activities are described in Sections 3.3.1–3.3.5:

3.3.1. Literature review

In every article, a short literature review about the state of the art of the research area of interest is presented. The academic publications utilized in the literature reviews were found using keywords on the SCOPUS database, along with backward and forward snowballing (Wohlin, 2014) procedures from highly cited and/or new articles in the field. Due to the rapid development pace of some of the technologies of interest in this study, such as AM, non-academic publications retrieved from technology websites and forums were also included.
Larger literature review activities were performed for the research clarification study in Article A to identify and evaluate existing areas or gaps that require research (Wohlin, 2014). In this article, a systematic literature mapping (Kitchenham and Charters, 2007) was performed by cross-analyzing and “matching” two neighboring research areas (research on DfAM methods and research on the introduction of AM in space products). Of the different methodologies for performing a literature review, a literature mapping study was preferred, as this approach focuses on broad research questions to review a substantial number of publications, aiming for publication classification to achieve a high understanding of the research area (Barn et al., 2017). The entries obtained through SCOPUS, snowballing, and non-academic publications were filtered by title, abstract, and then full-text content, based on appropriate inclusion criteria.

3.3.2. Workshops

Most of the data-gathering activities for Articles A, B, and C were performed through workshops for the RIQAM project, which involved the joint efforts of Swedish universities and aerospace companies. The distribution of data-gathering and validation activities through the workshops is presented in Figure 3.4. Five workshops and five follow-up meetings, attended by 10 experienced industrial practitioners from the participating companies, were carried out. The workshops were held approximately once every two months, with follow-up meetings set up between workshops for data and model validation purposes. The industrial participants were engineers (with 12 to 30 years of experience) working in PD at the participating companies. Observations and workshop results were documented through field notes and pictures, and they were subsequently transcribed and analyzed through content

analysis (Miles et al., 2013). Observations and results were then distributed to the participants of the workshop for discussion. Follow-up phone meetings were conducted with the participations for verification and exchange of statements.
The first workshop (W1) focused on presenting 10 designs for AM strategies (e.g., part consolidation or topology optimization) to the participants using examples. These strategies are summarized in Lindwall and Törlind (2018). The presentation of these strategies served as random stimuli (Cross, 2000) for the generation of novel concepts. Each company presented one case study product to be redesigned for AM during the five workshops. In the concept generation phases of the workshops, to mirror the current design activities in the three involved companies, no designs for an AM methodology were implemented (which are not supported by formal DfAM processes). A series of semi-structured interviews (Robson, 2002) were conducted between the workshops to understand the participants' own experiences designing for AM, and those insights were used to further develop workshop activities. In the second workshop (W2), FM techniques were implemented for continuing the design process. The workshop focused on the functional decomposition of the different case studies. Observations and studies from W1, W2, and their complementary meetings were utilized for the development of Articles A, B, and C. Observations from W2 were also implemented in the development of Article B.
Function models were developed with the function decompositions from W2. These models were created collectively by the researchers and industrial partners during complementary meetings, and they were validated and refined during the third workshop (W3). In W3, results from Articles A and C were presented and discussed for validation purposes. The rest of W3 was dedicated to discussions and reflections that served as the first data collection activities for Article B.
In the fourth workshop (W4), a plan and schedule for the data collection activities for Article B were established.
Finally, in Workshop 5 (W5), Article B was presented and discussed to validate its results.

	Article A	Article B	Article C
Workshop 1	D		D
Workshop 2	D	D	D
Workshop 3	V	D	V
Workshop 4		P	
Workshop 5		V	

D Data collection P Planning V Validation

Figure 3.4. Data-gathering and validation activities performed during the Radical Innovation and Qualification for Additive Manufacturing (RIQAM) workshops for the different articles in this thesis.

3.3.3. Interviews

To refine specific points and concerns raised during the RIQAM workshops, semi-structured interviews (Robson, 2002) were held with industrial practitioners for Article B. Most of the subjects interviewed were not participating in RIQAM, although they belonged to the participating companies. Semi-structured interviews were preferred, since the topics under study are complex and might have required follow-up questions and explanations to ensure their appropriate interpretation (Bell et al., 2018).

The interviews were performed following a set of predefined questions; however, the interviewees were encouraged not only to answer the questions but also to elaborate on specific points that they considered pertinent (Williamson and Bow, 2002).

When interviewees granted permission, the interviews were recorded and then transcribed; otherwise, data were collected through notes. To clarify the data and identify recurring themes, selective coding was implemented. Data reduction in the form of pattern matching and data displays was utilized to synthesize the findings (Miles and Huberman, 1994). The pattern matching involved the definition of categories based on topics identified before performing the interviews. The interview transcripts were then read, and quotes related to the identified categories were highlighted. The results from the coding were compiled in spreadsheets for comparison purposes. The quotes in the spread sheet were then condensed into a text document that was then sent back to the interviewees for validation purposes.

3.3.4. On-site industrial studies

The bulk of the data collection activities for Articles D and E was performed through a three-month study at one of the companies participating in the CHEOPS project to study the design process of an EPS.

In this study, two of the authors of Article D worked on-site, in close collaboration with the company's design team, where full access to real company data and the possibility of performing interviews and participating in their technical meetings was provided. One of the two authors already worked at the company in a supporting role, and the other author had an observer role in gathering data during the three-month period. Both authors invested the equivalent of 60 full working days (8 h/day) in the data collection activities.

The information gathered for this study was be divided into (1) information gathered from documented sources (documented information) and (2) information gathered through interactions with practitioners (tacit information).

The data collection of documented information was performed through the analysis of company internal documentation, including mission-specific documents (where and how the product will be utilized) and product-specific documents (design and test requirements to comply with the specific mission), which were used to build a function model of the EPS. Documentation regarding PD and testing was gathered and documented in preliminary lists. Later, those lists and further information collected about activity schedules were stored in program evaluation and review technique (PERT) diagrams.

Another portion of the data was obtained from the ESA's product, test, and qualification standards for space components, and it was used to complement the function model and PERT diagram.

In addition to the documented information, a series of meetings and semi-structured interviews were held with company practitioners. Most of the meetings were held for model (PERT and FM) validation purposes, while other meetings were held to gather formation about the duration, costs, and sequence of test activities.

The meetings and interviews lasted between one and two hours and were held with seven company practitioners with an average of 10 years of expertise in the areas of SE and the design, testing, and qualification of EPSs.

3.3.5. Solomon four-group study design

One of the simplest methods for evaluating the usefulness of a method or a tool is a two-group posttest experiment (Figure 3.5.a) (Trochim, 2021). In this experiment, one group applies the method or tool to perform a task, and the other group does not. The results are then compared based on preestablished metrics. However, this method does not provide a way to compare both groups' baselines; therefore, the results from these studies could be due to intrinsic differences between the two groups.

One approach to establish a baseline to compare both groups is to carry out a pretest-posttest experiment (Figure 3.5.b) (Trochim, 2021). In this experiment, both groups perform a pretest to establish their baseline results, which are then compared with the results obtained after applying the method or tool of interest. For example, when evaluating the usefulness of a design method for shortening design times in two different companies, a pretest would establish a comparison (baseline) of the current (without the tool) design times of each company.

Nevertheless, a drawback of this configuration is the difficulty of establishing whether the obtained results are due to the method or the "practice" obtained during the pretest.

The Solomon four-group design (Figure 3.5.c) (Sawilowsky et al., 1994; Trochim, 2021) is an experiment arrangement designed to assess the effects of a pretest. This arrangement requires four groups: Two of the groups use the method or tool, and two do not. Furthermore, two of the groups receive a pretest, and two do not.

The Solomon four-group study design was implemented in Article F for evaluating the usefulness of the methods proposed in this thesis.

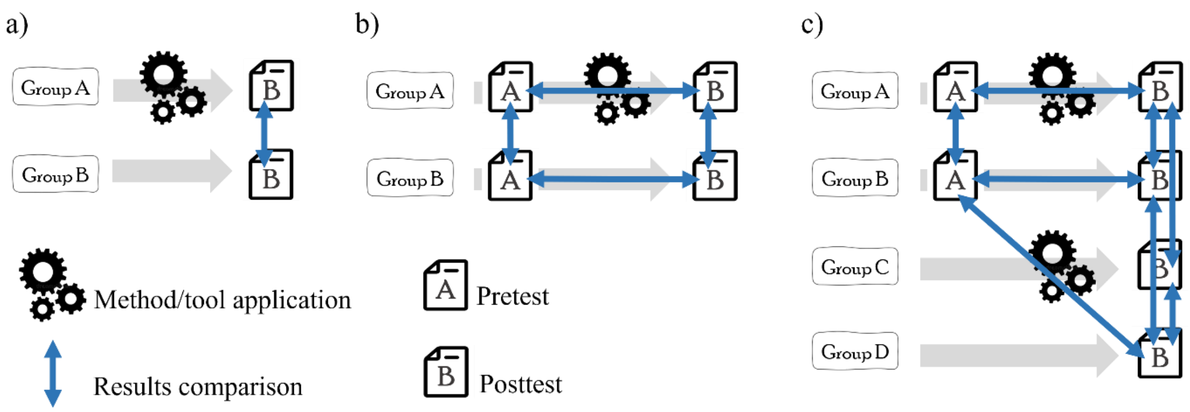


Figure 3.5. Comparison of experimental design methods. a) Two-group posttest experiment, b) two-group pretest-posttest experiment, and c) Solomon four-group design experiment.

The study was performed in the context of the DIDAM project, with the participation of 12 industrial practitioners.

4

SUMMARY OF APPENDED ARTICLES

4.1. Article A: Impact on design when introducing additive manufacturing in space applications

4.1.1. Article summary

In this article, the impact on the design process when introducing AM in space components is studied. Through a systematic literature mapping and an empirical study, the limitations and challenges of introducing AM in space components are matched with the existing design strategies for AM. The article points at “modeling” as a crucial design strategy in the context of DfAM.

From the systematic literature mapping and the empirical study, it is inferred that there is a lack of knowledge, technology development, and experience regarding the application of AM in space components.

During the empirical study, the largest manifested concerns related to quality and qualification: the nature and detection of manufacturing defects and their impact on performance, material behavior and capabilities, surface finishing, and geometric accuracy. Furthermore, there seems to be a misalignment between the industry needs and challenges on the one hand and the general focus of the design research community on the other. It is inferred that for AM to be introduced in space applications, space components should undergo a process of redesign. However, even if AM enables design freedom, practitioners exhibit a tendency to design products similar to those they know, due to the strong technology legacy from traditional manufacturing technologies. Moreover, total AM design freedom is not guaranteed, as this technology has several manufacturing limitations.

It is concluded from the findings that when designing for a new manufacturing technology, modeling techniques are important to exploit design exploration opportunities and to gain confidence in decision making. Systematic modeling techniques, such as FM (one out of three DfAM methodologies implement FM), can be a powerful support for organizing and implementing the little information available about a product and a technology. By implementing these techniques, available knowledge about AM can be used for extracting conclusions and analyzing the proposed concepts, thus enabling concept comparison.

4.1.2. Conclusions

To introduce AM in space applications, space components should undergo a process of redesign. However, even if AM enables unprecedented design freedom, total design freedom is not guaranteed, as this technology has several manufacturing limitations. Moreover, there is a lack of knowledge, technology development, and experience regarding the application of AM in space products. These results align well with several articles on the topic, such as work done by Salonitis (2016), Lindwall et al. (2017), and Dordlofva (2018). The aforementioned lack of knowledge combined with strong technology legacies leads to designs that are similar to their traditionally manufactured predecessors and that hence do not take advantage of AM design freedom.

When designing for a new technology, model-based design techniques can contribute to design exploration and confidence in decision making. However, as other authors have remarked (Lindwall et al., 2017; Dordlofva, 2018; O´Brien, 2018), to be relevant in the space industry, design techniques must have a holistic approach to PD and the product lifecycle to consider, early in the design phases, the needs of later PD process activities such as qualification.

4.1.3 Contribution to the thesis

The research conducted in this article served to identify the research gap for this thesis and to gain a better understanding of the space industry's design techniques for new technology implementation. The article points out that when designing for a new manufacturing technology, model-based design techniques are important to exploit design exploration opportunities and to gain confidence in decision making. As information is scarce in early phases of the design process, abstract product representations (such as function models) can facilitate the design process.

4.2. Article B: Drivers and guidelines in design for qualification using additive manufacturing in space applications

4.2.1. Article summary

In this article, factors are presented that impact or drive the qualification activities of products for space applications. These factors are named "qualification drivers" and are intended to serve as a baseline for developing design guidelines in the future to support the qualification of AM components. The results presented in this paper are based on 12 semi-structured interviews with two companies that manufacture space products in the European space industry. From this article, it is concluded that the market shift that the space industry is experiencing affects PD processes. Introducing AM in their portfolio, companies aim for design flexibility, cost and time-to-market reductions, and an increase in production volume while maintaining a high product quality. However, knowledge about AM capabilities is scarce, and the product outcome is sometimes unpredictable, which renders the qualification activities challenging and expensive.

Qualification is an integral, but expensive part of PD in the space industry. To mitigate time-consuming and expensive qualification activities for AM, qualification logics should be included and considered as design guidelines and requirements during early design processes. Unless the qualification activities or strategies are defined and qualification requirements are established when design decisions are made, the cost of qualification might become too high.

A DfAM methodology for the effective introduction of AM in the space industry must include DfQ guidelines to assist designers to deal with critical product features. The qualification drivers proposed in this article support the future development of qualification guidelines and qualification requirements. However, even if the qualification drivers are general enough to be applied to multiple products and business cases, there will not be one qualification logic that fits every AM component, as qualification is product and process dependent.

4.2.2. Conclusions

As previously reported, the market shift that the space industry is experiencing motivates the introduction of new technologies such as AM. By introducing AM, companies aim for design flexibility, cost and time-to-market reductions, and an increase in production volume while maintaining a high product quality. However, the knowledge about AM capabilities is scarce, and the product outcome is sometimes unpredictable. As qualification is an integral part of PD in the space industry, qualification activities must be considered early in the design process. Otherwise, due to the lack of knowledge and experience regarding AM, the cost of AM qualification might become too high. These results are aligned with previous literature pertaining to the field of qualification for AM in space components (Dordlofva and Törlind, 2018; O´Brien, 2018).

4.2.3. Contribution to the thesis

The research carried out for this article evidenced that a) in early design phases the knowledge about AM capabilities is scarce and b) the product outcome is sometimes unpredictable, which renders qualification activities challenging and expensive. The early modeling of qualification requirements can help to mitigate the cost of these activities.

4.3. Article C: Constraint replacement-based design for additive manufacturing of satellite components: Ensuring design manufacturability through tailored test artifacts

4.3.1. Article summary

In this article, as a basis for product redesign using AM, a methodology based on EF-M FM methods and constraint modeling is proposed. In this methodology, to redesign a product that is currently manufactured via traditional manufacturing methods, its original functions, DSs, and manufacturing constraints are identified and arranged in an EF-M tree. In this method, constraints are divided into two groups: manufacturing constraints (which are technology capability constraints) and functional constraints (related to performance). The process of constraint distinction facilitates the process of identifying DSs in the design that are only manufacturing (new technology) dependent and that can therefore be redesigned for AM.

With the constraints classified, the original manufacturing constraints are removed and replaced with manufacturing constraints for AM. Hence, the design space is freed and then constrained again according to AM limitations. From this process, a new AM function model is developed and utilized for designing a new part geometry for AM.

As constraints are related to the AM process of choice, different AM processes present different constraints. Constraint modeling and replacement enables the identification of constraints that are not entirely well defined (information designers know is missing; i.e., known unknowns [KUs]); for example, there is a threshold surface inclination angle below which support structures are needed, but that angle might be unknown. To improve constraints definition,

product-tailored test artifacts are proposed. Manufacturing test artifacts provides the required information and evidence of new AM constraints that were previously unknown (i.e., unknown unknowns [UUs]). For instance, to avoid the generation of unmelted particles between closely located outlets, the outlets must be placed 30° apart.
This methodology was applied in a case study featuring a satellite subcomponent.

4.3.2. Conclusions

The methodology proposed in this article aims at redesigning components for AM, not only taking advantage of AM design freedom but also considering AM limitations, as suggested by authors such as Boyard (2015) or Pradel et al. (2018).
FM methodologies allow for an organized display of product information that enables a deep understanding of product architecture. The nature of EF-M modeling techniques permits the identification and separation of design constraints that depend on product performance from constraints that depend on the technology applied. This separation provides the designer with an effortless identification of product features and geometries that are manufacturing dependent and can hence be redesigned for AM. Constraints classification enables constraint replacement, which facilitates the identification of constraints where more information is required (i.e., KUs) and constraints that were previously unknown (i.e., UUs).
Moreover, the process of identifying traditional manufacturing constraints and then replacing them with AM constraints can support the acknowledgment and enable the removal of the carried-over knowledge and experience that designers have about traditional manufacturing technologies. As suggested by the work of (Kumke et al., 2016; Seepersad et al., 2017), acknowledging carried-over practices can be the first step toward mitigating practitioners' tendency to design products similar to those they know.

4.3.3. Contribution to the thesis

The research conducted in this article served the purpose of developing and testing the first part of a model-based method for identifying and modeling KUs and UUs through the process of constraints replacement. The methodology is based on function and constraint modeling, since their abstract product representation is suitable for conceptual stages where product information is scarce. Moreover, their level of abstraction facilitates model evolution and adaptation as knowledge about new technologies and their requirements continues to be developed.

4.4. Article D: Design for test and qualification through activity-based modeling in product architecture design

4.4.1. Article summary

VVT phases take up a significant portion of the time to market for high-performance, critical products in the space industry, especially when introducing new technologies. However, as VVT activities are normally treated as standard procedures, they tend to be independent of product architectural design decisions. When implementing new technologies, however, VVT procedures may differ from those implemented in regular design scenarios, and the early estimation of qualification costs and duration is problematic.
In this article, a computer-assisted modeling method that models VVT activities in relation to early product architecture designs is proposed and demonstrated in a case study for EPSs for

satellite applications. Product architecture alternatives, modeled in an FM, and test schedules and costs, modeled in a PERT diagram, are connected through the identification and quantification of VVT drivers and driver rates, with the purpose of designing products with affordable VVT phases.
The method was utilized to model VVT phases for a 5-kW hall thruster with a conventional power processing unit (PPU) configuration. Later, implementing that model, VVT procedures were integrated into the conceptual design and evaluation process of a 20-kW thruster design. Two design alternatives for the 20-kW thruster were evaluated—one with a conventional PPU arrangement and one with a new direct drive (DD) technology. Different VVT schedules were also evaluated.

4.4.2. Conclusions

The link between the FM with the product architecture and the PERT diagram with the VVT schedule enables the integration of VVT procedures into the conceptual design and evaluation of product architectures. The link is achieved through the identification and quantification of VVT drivers and driver rates, which are factors that drive the design, costs, and duration of VVT activities.
It is proposed that by defining VVT drivers, the defining characteristics of VVT procedures can be quantitatively modeled and integrated into a design study where alternative technologies and concepts are investigated. Therefore, the method can be applicable for various design situations where the choice of technology is strongly dependent on the qualification procedure. Identifying and quantifying drivers and driver rates enables the identification of test-intensive components, modules, and subsystems, allowing one to establish design specifications to restrict the type and number of components in a design for developing products with affordable VVT phases. The opportunity to establish requirements and specifications for the VVT activities to design affordable VVT phases is also highlighted, along with the recommendation of risk assessment strategies related to partially performing or completely removing specific VVT activities. Moreover, representing the PERT diagram as a DSM enables the implementation of clustering algorithms to optimize the schedule.

4.4.3. Contribution to the thesis

This article complemented a function model representation with a PERT schedule diagram and activity model, setting up the baselines for a holistic modeling strategy aiming at front loading the conceptual stage with data from the whole PDP. High-performance architectures are sometimes outweighed by expensive or time-consuming downstream phases. A holistic modeling framework enables the identification of design requirements and specifications related to later PDP phases, such as manufacturing, verification, or validation phases.
This study introduces the importance of risk assessment in the context of design decision making and the possibility of redesigning later PDP phases concurrently with the product architecture design.

4.5. Article E: Fuzzy model-based design for testing and qualification of additive manufacturing

4.5.1. Article summary

The introduction of AM in the space industry is hindered by the difficulty to design an AM product that fulfills the stringent V&V standards of the industry. The advantages of AM are usually based on nominal values of material properties. However, as the variation in material properties once manufactured is less predictable than for more established manufacturing methods, such as forging and casting, this causes a problem for designers. Accounting for such uncertainty during design might require large design margins. In addition, the lack of experience in AM technologies renders experts' assessments of AM components and the establishment of safety margins difficult. Unexpected V&V difficulties resulting in expensive and lengthy redesign processes might consequently arise.

To reduce the risk of unsuccessful V&V phases, engineers might perform copious time-consuming and expensive specimen testing in early phases, or they might establish overconservative design margins, overriding the weight reduction benefits of AM technologies. In this article, a model-based design for a V&V method is proposed for the conceptual design of AM space components. The objective of the method is to support the design of products with a high likelihood of successful V&V phases, thereby reducing the likelihood of redesign loops. The method utilizes fuzzy logics to systematically account for experts' assessments of the variation in AM properties and to provide an early quantification of a product's likelihood of successful V&V. If needed, a more detailed assessment of qualification likelihood can be performed through targeted test campaigns, but the preliminary experts' assessments help to reduce the need for test campaigns. The method is demonstrated with the DfAM of gridded ion thrusters for satellite applications.

4.5.2. Conclusions

The novelty of the method lies in the modeling and quantification of the likelihood of successful V&V phases and their integration into design studies and concept evaluation.

In regular design scenarios, when introducing new technologies in the space industry, hundreds of samples are tested to achieve strong statistical knowledge bases before the design and V&V phases. However, this process can be time and resource consuming.

In this study, experts' assessments and qualification maps are combined to identify when and if predesign testing is necessary, thus reducing the time and cost spent on test activities while still ensuring the development of a qualifiable product.

Qualification maps, which indicate which design parameter combinations yield qualifiable products, were proposed and proven to support design activities for single components and for product assemblies. Moreover, qualification maps allow designers to look over their own aggregated judgments and discuss the accuracy of their initial assessments. The method can be applied in various design situations where the implementation of novel technologies, such as AM, can hinder innovation due to the lengthy tests that are required to ensure the design of a qualifiable product.

This study goes beyond what other studies have reported, enabling V&V phases to be included in sensitivity studies, trade-off studies, and other digital experiments where a range of concepts must be simultaneously evaluated.

4.5.3. Contribution to the thesis

The study carried out in this article enables V&V phases to be included in sensitivity studies, trade-off studies, and other digital experiments, through the introduction of qualification likelihood and risk. Qualification likelihood and risk are presented in qualification maps, where the need for and importance of performing tests over specific design parameters are evaluated. The initial risk assessment is performed by experts' judgment; however, qualification maps allow designers to look over their own aggregated judgments, discuss the accuracy of their first assessments, and decide whether further testing is needed.

4.6. Article F: Reducing design uncertainty through model-based collaborative design methods when introducing new technologies: A Solomon four-group design study

4.6.1. Article summary

When introducing new technologies in product design, uncertainties regarding technology feasibility and the way technology introduction impacts the whole PDP hinder the establishment of appropriate design specifications during conceptual stages. Ill-defined design specifications can lead to expensive and time-consuming redesign loops.

Uncertainties about the new technology can be known (i.e., UKs: information designers know is missing) or unknown (i.e., UUs: information designers do not know is missing).

On the one hand, strategies for dealing with known uncertainties are well established and include, for example, test campaigns for data gathering. Unknown uncertainties, on the other side, are difficult to identify, as practitioners do not know what is missing.

Failing to identify unknown uncertainties can lead to unpleasant and expensive surprises that arise late in the PDP, rendering the introduction of a new technology an expensive and time-consuming endeavor.

Previous articles in this thesis have proposed an integrated design platform and design methods to support the identification and modeling of uncertainties during conceptual phases. The design platform is composed of a function model of the product architecture linked to a PERT diagram of the product's and system's validation activities. Each validation activity is connected with the respective DS in the FM. Moreover, both the FM and the PERT display a color-coded assessment of the risk of not performing each validation activity. In this article, the usefulness of such a platform and associated methods are evaluated using a Solomon four-group design study featuring the design of satellite components for AM.

4.6.2. Conclusions

The platform and constraints replacement method are evaluated with a Solomon four-group design study involving 12 experienced industrial practitioners and featuring the design of satellite components for AM.

The results of the study suggest that the proposed platform and constraints replacement method are useful for identifying design and schedule uncertainties and for proposing measures to address them. Moreover, the design platform enabled discussions about activity risk and its use to propose measures to deal with uncertainties without compromising product quality while maintaining an affordable validation schedule.

However, a drawback of the constraints replacement technique is that uncertainties are discovered as long as their traditional technology counterpart is well modeled. Nevertheless, the need to make "uncertainties seeking" a common practice is highlighted in this study—an organization that is actively looking for uncertainties is more likely to identify them in a timely and resource-efficient manner.

During the experiments, it was also observed that unknown uncertainties are not always "unknowable." Sometimes, they are aspects that have escaped the minds of practitioners or that no one has bothered to investigate.

Due to the small sample size and the artificial design setting in which the studies were performed, the obtained results and conclusions cannot be generalized. Nevertheless, the findings were still useful, as they were presented to the participants and enabled a fruitful discussion about design support platforms and a culture of uncertainty seeking.

4.6.3. Contribution to the thesis

The experiments performed in this article assess the usefulness of the proposed digital design platform and the constraints replacement process in an industrial context. This assessment is crucial for strengthening the thesis validation claims in Chapter 7. Moreover, in this article, the limitations and shortcomings of the proposed platform and methods are identified and highlighted, thereby enabling the establishment of improvement guidelines to apply in future work.

5

RESULTS

5.1. Main knowledge gaps that hinder the introduction of new technologies in the space industry

The market shift that the space industry is experiencing impacts PD processes (Article A, Article B). By introducing new technologies, companies aim for design flexibility and cost and time-to-market reductions while maintaining a high product quality (Article A, Article B). However, when introducing new technologies, previous technical knowledge might lose its relevance and applicability (Article B, Article C, Article F).

Every research project in which the work for this thesis was carried out, aimed at increasing the knowledge about new technologies for their later application by the participating companies. Project RIQAM, for instance, focused on increasing companies' knowledge about manufacturability and qualification with AM technologies (Article B, Article C), for example the establishment of AM design constraints such as "*Minimum material defects density*" and "*Minimum overhang angle to avoid support structures*," which would support the establishment of AM engineering specifications, thus reducing redesign loops. Moreover, after identifying AM constraints and specifications, traditional qualification activities can be tailored for AM, or AM-specific qualification activities can be established, such as the implementation of computerized tomography (CT) scanning techniques for defect measurements.

The lack of knowledge about new technologies hinders the establishment of engineering specifications, and development projects with new technologies can consequently become longer and more expensive than those with traditional technologies. Ill-defined specifications often lead to expensive redesign loops (Article C) or prolonged test phases to ensure product quality (Article B). In Article C, the lack of knowledge led to the design of an AM flow connector that, when manufactured and removed from the building plate, had an uneven bottom. After a redesign loop, a new engineering specification related to bottom flatness was chosen.

In Article B, practitioners stated that the lack of knowledge about AM capabilities leads to prolonged VVT phases.

In project CHEOPS, the introduction of new technologies for high-power hall thrusters was considered (Article D, Article E). In this context, Article D focused on the impact that changes in the architecture design have on VVT activities and their schedule for the introduction of new DD technologies in EPSs. However, the idea of implementing DD technologies on high-power thruster units was abandoned, as technology uncertainties resulted in VVT phases that were not affordable (Article D).

In Article E, the likelihood of passing a qualification test was used as a metric for establishing engineering specifications related to different design parameters. Establishing specifications that ensure product quality would reduce redesign loops due to failed qualification tests.
The IDAG, DIDAM, and DigiQUAM projects addressed the knowledge gaps related to AM technologies' capabilities and the design of high-quality, repeatable AM products (Article F).
In Article F, practitioners stated that the lack of knowledge about AM capabilities leads to prolonged VVT phases due to ill-defined specifications. For example, on a heat exchanger, material defects could lead to leakage problems. As the density of defects might be difficult to predict or control, extra tests such as CT scans must be performed to detect those defects, thus prolonging the VVT phases.
Defining engineering specifications is always challenging, especially for inexperienced designers, as it requires extensive, multidisciplinary knowledge about the product and the PD process. However, as knowledge and experience about new technologies are limited, establishing requirements is challenging even for experienced designers (Article B, Article D, Article E, Article F).
The introduction of a new technology affects PDP activities. In this context, as VVT phases for space products account for more than 40% of the PD costs, the impact that new technologies have on these activities was highlighted in the RIQAM and CHEOPS projects (Article A, Article B, Article D, Article E).

5.1.1. Summary

Section 5.1 aims at answering the following research question:

RQ1: What are the main knowledge gaps during conceptual stages that hinder the establishment of engineering specifications for the introduction of new technologies in the space industry?

Throughout the projects on which this thesis is based, the identified knowledge gaps for technology introduction in space products can be grouped into two categories:

1. Engineering specifications related to technology capabilities: what is feasible to attain when introducing a new technology (Article A, Article B, Article C, Article F). The difficulty in establishing engineering specifications relates to the establishment of design margins and the consequent design of high-quality optimal products.
2. The way the new technology (and new engineering specifications) will affect the VVT phases. The VVT phases are already one of the main contributors to the total cost and duration of the PDP for space products. Uncertainties related to engineering specifications for new technologies are expected to increase the cost and duration of the VVT phases, which can render the introduction of a new technology unaffordable (Article D).

From an engineering design (ED) theoretical point of view (illustrated in Figure 5.1), a company can be proficient in developing certain types of DSs, implementing specific technologies to satisfy the FR of their product portfolio. Each DS has associated constraints and engineering specifications. When a new product or a variation of a former product is designed, new engineering specifications are established that respect the design space bounded by the Cs. These constraints and the eligible engineering specifications are well known and have solid, well-established VVT phases (see Concepts A and B in Figure 5.1).

When a new technology is introduced, the new DSs are expected to have a different set of constraints and hence different engineering specifications. Some of these constraints and specifications might be similar to those of the previous technology, but others might be unknown (see Concept C in Figure 5.1).

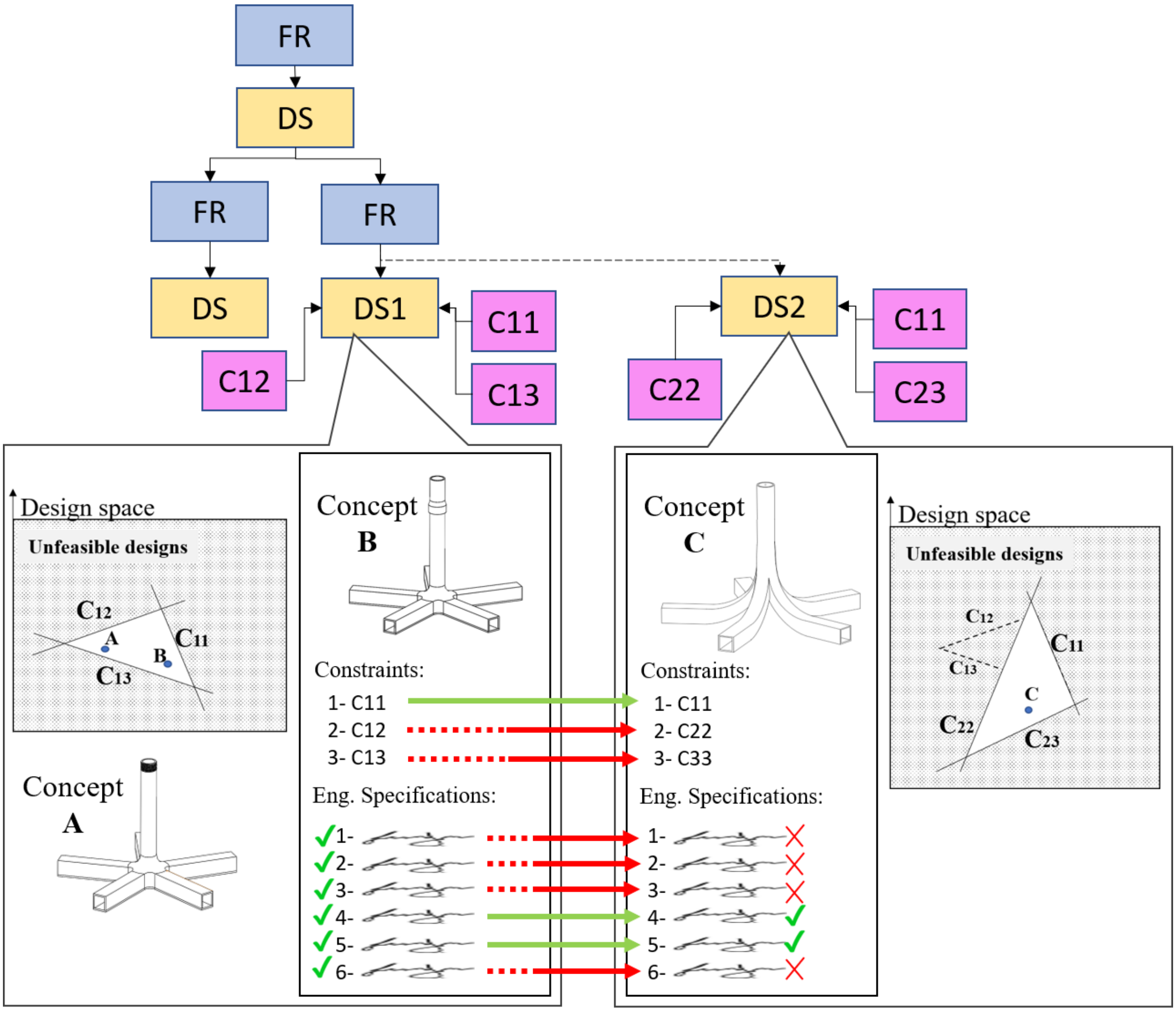


Figure 5.1. When a new technology is introduced, the new design solutions (DSs) are expected to have a different set of constraints and hence different engineering specifications.

5.2. Factors that hinder data gathering for the establishment of engineering specifications

To deal with the lack of knowledge, or uncertainty, about a technology's technical capabilities, three coping alternatives were identified in the previously mentioned studies (Article C, Article E, Article F):

1. Radical implementation of the new technology (which correlates with increased performance) coupled with intensive data-gathering or test campaigns: Develop a novel design, and fill the knowledge gaps by testing a large variety of specimens early in the PD process (establishing well-defined engineering specifications to ensure product quality) or by extending the VVT phases. Either way, this approach substantially impacts the cost and duration of a PD process. This strategy may be acceptable for technology demonstrations and/or cost-insensitive applications.
2. Conservative implementation of the new technology coupled with reduced test campaigns: Deliberately avoid testing many specimens (and the associated costs), and develop a conservative design. In this case, the manufacturer develops a product with the expected quality but misses the opportunity to fill knowledge gaps and achieve a more radical—and perhaps better—design. Tests are still performed (but in lower numbers), and some late redesign efforts and extended VVT activities are still expected due to uncertainties or problems discovered late in the PDP. This is known as a "fail-safe" strategy.
3. Radical implementation of the new technology coupled with marginal testing: Deliver a novel and radical product without performing much testing; this type of product can only be considered for applications where failures can be acceptable. This alternative often results in either expensive redesign efforts due to failed manufacturing or VVT phases or components with high failure rates. Such a strategy is rarely acceptable in space applications to date but is generally denoted as a "safe-fail" strategy.

In two of the above-mentioned alternatives, there seems to be a trade-off between performance increase (from technology implementation) and qualification ability at affordable costs. In the first alternative, performance is at the highest; however, a qualifiable product undergoes a) extremely expensive data gathering to establish well-defined engineering specifications that ensure the design of a high-quality product or b) extended VVT phases. Costs related to data-gathering activities are reduced in the second alternative, but at the expense of performance, which is reduced.

The price of not gathering data is also high, as suggested in the third alternative, due to the high failure rates.

One of the main factors that hinders data-gathering activities for the establishment of engineering specifications is, evidently, the cost and long duration of the data collection activities, performed during early test campaigns or during later VVT activities.

The aforementioned three alternatives imply that the technology uncertainties are known (i.e., KUs). However, not every uncertainty is known; many of them are unknown (i.e., UUs).

For example, in Article C, at the beginning of the design process, it was known that AM machines have a minimum manufacturable wall thickness that should be included in the engineering specifications list. However, that thickness was unknown (i.e., KU). On the other side, the fact that the AM process would affect the connector bottom flatness was unknown (i.e., UU) at the beginning of the design process.

As previously mentioned, when the KUs are identified, data can be obtained through test campaigns or experts' assessments (Article C, Article D, Article E) to transform them into known knowns (KKs).

The UUs, however, are difficult to identify, since they are pieces of information that practitioners do not know they do not have (Article B, Article F).

These uncertainties lead to the tendency among designers to design products with similar features (similar engineering specifications) to their predecessors, as the unknown data gaps about the new technologies are filled with knowledge carried over from previous design projects (Article A, Article C). As previous data are not always applicable to new design contexts, ill-defined engineering specifications are established.

Article C features a redesign for the AM of a flow connector that is traditionally machined from a metal block. The redesigned connector had an AM-enabled curved designed to reduce pressure losses, and it was attached to a satellite interface in the same way as the old (machined) design: through two separated "ears." However, the AM process generated support structures on the bottom of the attachment "ears," and as the support removal procedure was manual, it was difficult to ensure that, after post-processing, the flow connector would have a flat, leveled bottom. In this case, the assumption that a design feature that fitted the old design would fit the new AM design costed a design iteration. The effect that the AM process would have on the flatness characteristics of the connector bottom was an uncertainty that was unknown when the design process started.

Development projects usually have a portion of the budget (contingency budget) allocated to deal with unexpected costs, such as unpredicted redesign loops. However, as pointed out in Article E and Article F, not addressing the UUs during conceptual stages can lead to the establishment of inadequate contingency budgets and the failure of development projects. As highlighted in Article F, many approaches exist to find UUs (transforming them into KUs) in the project management literature, but they are rather "high level," as they do not pertain specifically to finding engineering specification-related UUs.

Both UUs and KUs can be sources of ill-defined engineering specifications (Article C, Article E, Article F). In the case of KUs, awareness of the uncertainty does not guarantee its early resolution, as KUs can sometimes be left uncertain. Moreover, not every KU is worth being transformed into a KK, as the required data-gathering activities can be resource intensive (Article C, Article F), and the uncertainty might not present a high failure risk. It is consequently inferred that not every ill-defined engineering specification poses a risk to the VVT budget and schedule. However, to be able to identify this type of specification and make these types of decisions during the conceptual stages, it is necessary to model VVT phases and the risk associated with ill-defined engineering specifications (Article E, Article F).

5.2.1. Summary

Section 5.2 aims at answering the following research question:

RQ2: What factors hinder data gathering for the establishment of specification requirements related to technology capabilities and their impact on the V&V schedule?

The following aspects hinder data gathering for establishing engineering specifications: the high costs and long durations of the data-gathering procedures, whether through data-gathering campaigns (to transform UKs into KKs) or through redesign loops (due to KUs that were consciously left undefined or due to UUs).

Cost-effective methods are hence needed to facilitate a) the identification of UUs (transformation into KUs) related to engineering specifications for technology capabilities and b) the subsequent resolution of KUs (transformation into KKs).

5.3. A cost- and time-efficient method for identification and resolution of uncertain engineering specifications

There is a need for cost- and time-efficient strategies for (1) identifying uncertainties about engineering specifications (i.e., transforming UUs into KUs) and (2) resolving uncertainties (i.e., transforming KUs into KKs).

Previous literature reviews (Article A) have suggested that FM techniques enable the modeling of product FRs, the embodiment of alternatives or DSs, and constraints that limit the design space and highlight how the system should fulfill its requirements, thus indicating which engineering specifications "are allowed." In addition, as presented in Article C and Article F, the function model representation allows for the inclusion of different constraints, such as manufacturing and test constraints, which represent the threshold values for engineering specifications.

In Article A, FM is recognized as one of the most popular and convenient modeling strategies to facilitate idea generation and innovation with new technologies.

However, as with every model representation, the accuracy of its representation depends on the quality of the information on which the model is based. In the case of a new technology introduction, not every engineering specification is well defined; in fact, many of them have KUs or UUs.

To shed light on specification uncertainties, this thesis proposes the implementation of constraint replacement techniques and the implementation of holistic modeling environments.

5.3.1. Constraint replacement technique

The constraints replacement technique is introduced in Article C and revisited and validated in Article F.

As proposed in this thesis, to introduce a new technology to a product based on a traditional technology, the product's original functions, DSs, and constraints are identified and arranged in a function model. The constraints are divided into different groups according to predetermined categories, such as constraints related to technology capabilities, product performance, and test activities, among others. This process of constraint distinction facilitates the identification of DSs in the design that are only dependent on new technology and that can therefore be redesigned.

When the constraints are classified, those that are technology dependent are removed and replaced with their counterparts for the new technology. For example, in Article C, the constraints related to manufacturability for machining technologies are removed and replaced by manufacturing constraints related to AM technologies. Article F includes the constraint replacement technique applied to test-based constraints as well. When redesigning the flow connector or the heat exchanger, participants implemented the constraint replacement technique to assess whether test-related constraints that were relevant for machining techniques were still relevant for AM.

Some of those constraints are well defined (i.e., they are KKs), and others are known to be uncertain (i.e., they are UKs). For example, for AM technologies, there is a threshold surface inclination angle below which support structures are needed. Different AM technologies and machines have different manufacturing capabilities and hence different angle limitations. Modeling this constraint points out the need to define this threshold angle for the specific AM technology and machine of interest.

Moreover, the constraint replacement technique provides a systematic procedure for identifying and gathering engineering specifications' unknown uncertainties by means of a guided and detailed technology comparison.
In Article F, implementing the constraint replacement procedure, practitioners were able to identify more UUs than through traditional documentation-heavy methods. In addition, during the experiments, some UUs were identified only with the constraint replacement procedure.
The replacement process is particularly useful when practitioners' experience is low, although it was also recognized as useful for experienced practitioners, as it establishes a starting point for discussions and idea generation (Article F), which can reveal additional UUs.
An additional benefit of constraint replacement is that the process of identifying and modeling constraints for traditional (legacy) technologies and then replacing them with new ones can support the acknowledgment and enable the removal of carried-over knowledge about traditional technologies. Acknowledging carried-over practices can be the first step toward mitigating practitioners' tendency to design products similar to those they know (Article C).
A possible drawback of this technique is that UU constraints about the new technology are discovered as long as their traditional technology counterpart is well modeled. The benefits obtained from the function model are related to the model's depth, breadth, and fidelity (Haskins et al., 2015). This was observed in Article F, where practitioners using the replacement method for UU identification missed some of the well-known uncertainties encountered when designing for AM, such as "*Min. feature size to enable removal of powder*" and "*Part geometry to enable removal of support structures (AM)*," as they did not have a direct machining counterpart.
In Article F, it was also observed that many uncovered UUs were aspects of the design process that had escaped the minds of the practitioners at the time of the experiment.

5.3.2. Constraint replacement in holistic modeling environments

The process of modeling technology-related (technology capabilities, test, manufacturing, etc.) constraints aids in the gathering and documenting of KUs. The process of constraints replacement helps to identify technology-related UUs, which then support the establishment of appropriate engineering specifications.
However, as mentioned in section 5.3.1, the benefits obtained from the modeling strategy are related to how wide, deep, and true the model is.
Article C proposed constraints classification and the inclusion of both performance- and manufacturing-related constraints in the function model. This multidisciplinary approach (considering manufacturing constraints already during conceptual stages) enables the inclusion of manufacturing trade-offs for design decisions during conceptual stages and the establishment of manufacturing-related engineering specifications. This inclusion allows designers to plan or perform specific, product-tailored test campaigns during development stages to shed light on manufacturing uncertainties in a cost- and time-efficient manner (Figure 5.2).
For example, in Article C, the AM minimum surface inclination angle manufacturable without support structures was identified as a KU and transformed into a KK through targeted testing. Manufacturers are often aware of this angle constraint but do not know its exact value. A product-tailored test campaign focuses on manufacturing test artifacts with geometries representative of those in the product and would explore the manufacturability of relevant surface angles.

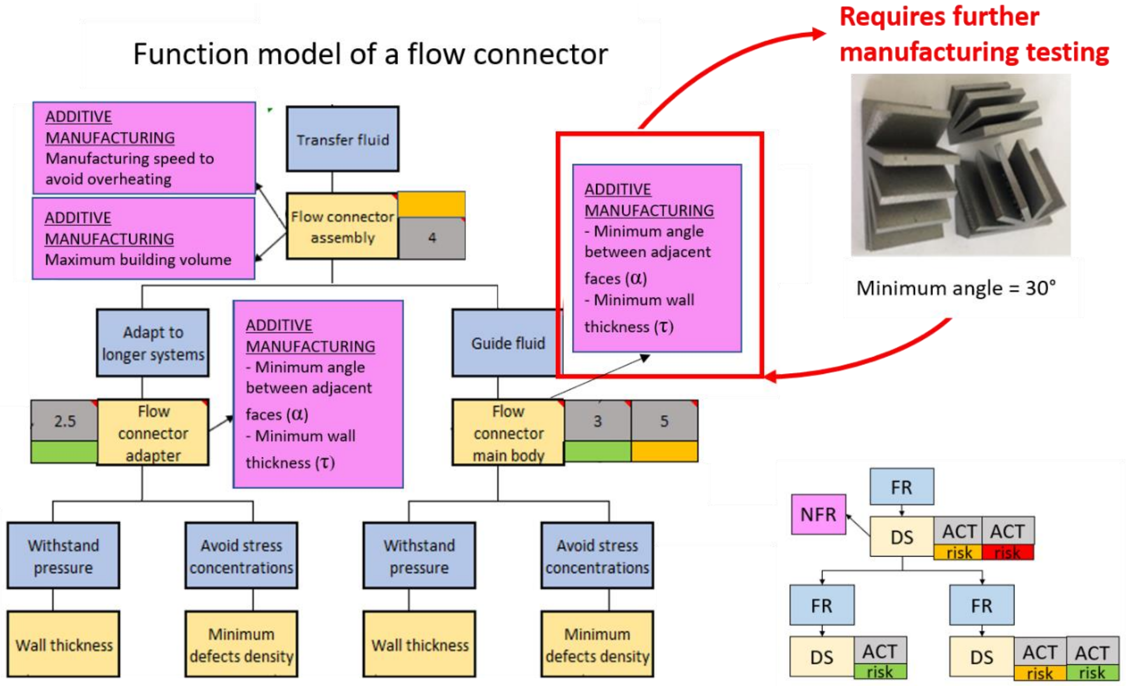


Figure 5.2. Function model with multidisciplinary constraints and the need for further testing.

In this way, test efforts might be increased during the development stage, whereas expensive redesign loops due to failed manufacturing processes are reduced.

Product-tailored test artifacts can also reveal UUs. For instance, after manufacturing test artifacts in Article C, it was discovered that to avoid the generation of unmelted particles between the closely located outlets of the flow connector, the outlets must be placed more than 30° apart. However, unveiling UUs "by chance" is not cost- or time-efficient.

In Article D, the function model representation was complemented with activity and schedule models. This article features the redesign of EPSs to introduce a new DD technology. An FM was built for the conventional EPS architecture; this model was then linked to a PERT diagram containing the schedule of the qualification activities for the EPS.

To enable the assessment of the impact that a future technology would have on the EPS architecture and the test and qualification (T&Q) schedule, the duration and cost of the qualification activities were modeled. Modeling these activities facilitated the identification of the parts of the product architecture (components, subsystems, systems, etc.) that drive qualification costs and times, and it enabled the assessment of the test schedule and cost of future EPS architectures with new technologies. These results are in line with Article B, where practitioners expressed the need to include T&Q activities during conceptual stages to design products with affordable qualification phases.

In Article D, the high costs of the T&Q phases for the DD architecture were partly associated with the way in which the DD technology disrupted the T&Q phases.

The DD configuration changed the EPS' architecture not only at a component level but also at a subsystem level. DD architectures require a modification of the PPU subsystem interfaces with the power generation system (PGS) that leads to changes to the PGS components as well. These changes lead to additional and expensive test activities that disrupt the whole T&Q schedule, making it too long and expensive.

Linking the FM with the T&Q PERT diagram enables the establishment of specifications related to the number, type, and combination of components allowed in an architecture in order to have affordable T&Q phases and an affordable product in return. In Figure 5.3, a schematic of the FM-PERT connection is presented.

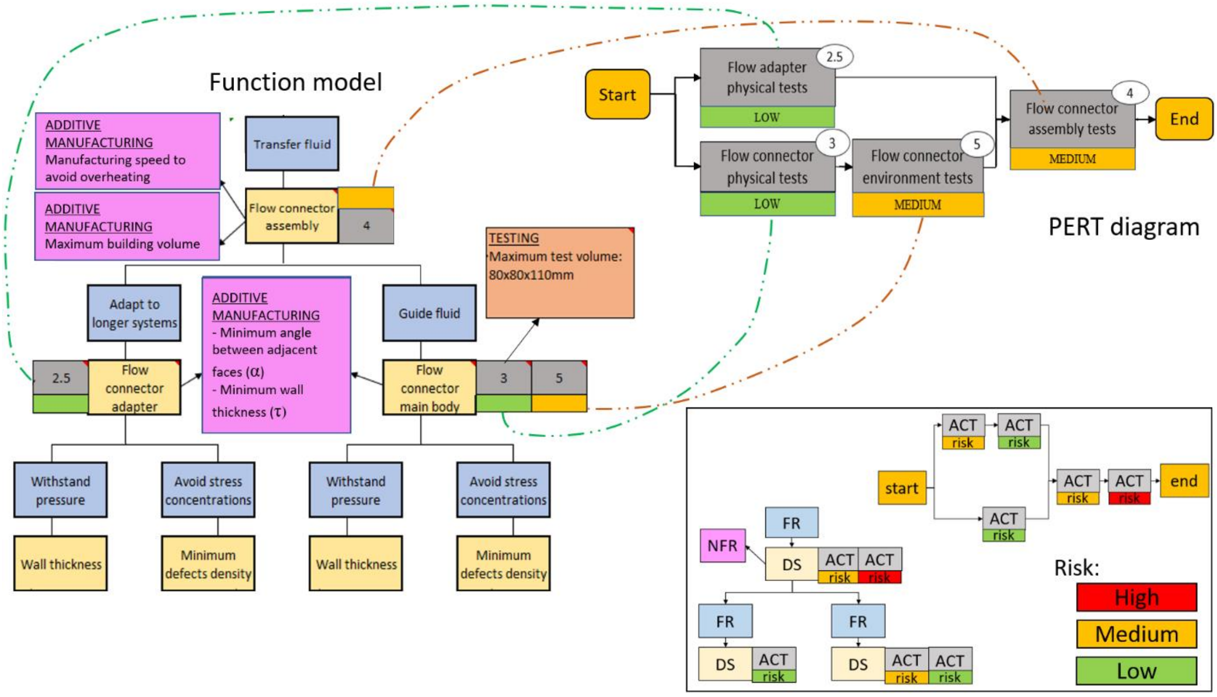


Figure 5.3. Function model from Figure 5.2 connected to a program evaluation and review technique (PERT) diagram.

This approach might increase the duration of the conceptual stage, but it supports the design of products with affordable T&Q phases, which generally make up to 40% to 60% of the total PD costs. Moreover, it enables the concurrent design of a product architecture and its respective T&Q phases. In Article F, for instance, the implementation of the FM integrated with the verification activities PERT diagram enabled the simultaneous assessment of product design alternatives and an assessment and redesign of their verification phases.

Article E follows the same principle of raising quality of decision making in early PDP phases through experts' assessments of qualification likelihood and targeted testing but reducing expensive redesign loops due to failed qualification activities.

The concept of a qualification map is introduced in Article E. In these maps, a combination of product design parameters, such as surface inclination angle (α) and wall thickness (τ), is mapped against qualification ability. Qualification-related engineering specifications could be defined as "Allowed α and τ combination: (τ ≥ 4mm AND (80 ≤ α ≤90 OR 0 ≤ α ≤10))," denoted by the green areas in Figure 5.4. Products in these areas are likely to pass the qualification test. The orange areas in the map represent parameter combinations where the available data are not sufficient to decide whether the parameter combination should be green or red. The delimitation of the green, orange, and red areas is roughly determined through experts' assessments and refined by targeted test campaigns. Assessments about qualification likelihood can be combined with a comprehensive analysis of the consequences of product failure to estimate the risk of component failure.

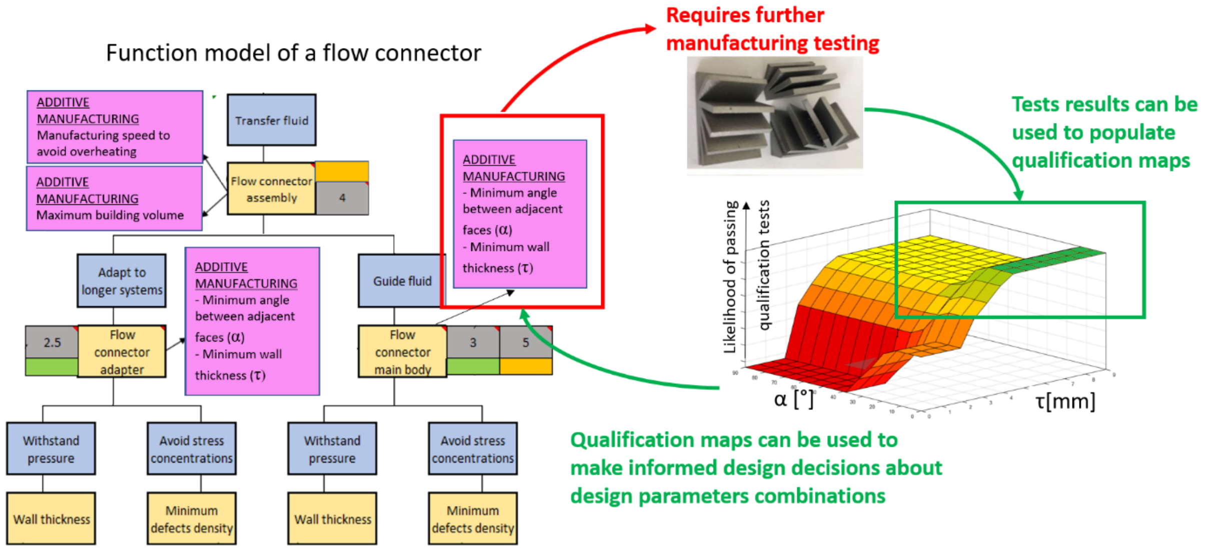


Figure 5.4. Function modeling (FM) with a constraint showing a qualification map.

However test campaigns to define those boundaries are not always necessary. If a design alternative is superior to others in aspects such as performance but is located on a boundary in the qualification map (orange area), then this is an indication that the design alternative might not pass a qualification test. In this case, the designer must analyze which strategy is more convenient: either perform targeted tests to increase the resolution of those boundary areas, which might be too expensive and time consuming, or pursue a different design.

The assessment of qualification failure and the use of qualification maps highlight that not every KU is worth the resources and time necessary for their transformation into a KK.

It can be rightfully argued that in the case of Article C and Article E, the level of detail at which constraints were modeled to design test artifacts aimed at producing data that will be used in later design phases, but that amount of detail is of little to no use in early conceptual design phases. However, the capabilities to model constraints are still interesting during early design phases where the models can be used for high-level estimations of the need for future test activities and their approximate cost and duration.

Qualification likelihood, combined with a study about product failure consequences, can enable the estimation of the risk (risk = likelihood*consequence) of not performing a certain qualification activity to reduce costs or expedite the qualification processes.

As observed in Article D, linking the architecture model to the qualification schedule enables one to assess the impact that architectural changes have on the test schedule and to make design choices that would reduce overall lead times and costs.

Article F takes the assessment proposed in Article D one step further through the inclusion of qualification risk analysis (red, green, and orange squares in Figure 5.2) in both the product architecture model and the qualification schedule model.

This assessment enables the visualization and identification of the parts of the product architecture that can be redesigned without altering the test schedule (the respective test activities are not part of the test schedule's critical path) and those whose redesign would impact the test schedule. In this context, if a test activity is delaying the test schedule and the risk of not performing this activity is low enough, then the design platform enables decisions about the removal or redesign of the activity. For example, the test activity could be removed, thus accepting the failure risk; the test could be removed, while the design could be made more robust; or the test could be removed, while the manufacturing process could be monitored more closely.

The main benefit of connecting the FM with PERT diagrams to create a holistic modeling environment is the consideration of late PDP phases during conceptual stages. This consideration enables the inclusion of those phases in design requirement trade-off analysis procedures.

Another benefit of holistic modeling environments is that they act as a model-based database for product information (Article F). This database can be reused to develop future products or product families. In DigiQUAM, for the development of the steering knuckle, it was necessary to obtain precise data about the relation between surface inclination angle and surface roughness. Several test artifacts were developed and manufactured to gather this information. Two of the three participating manufacturing companies declared that these types of data had been obtained for previous projects. However, the data were not documented, and the manufacturing tests had to be performed again.

This type of modeling environment is also adaptable and flexible and can evolve over time as the available information about new technologies increases (Article C, Article F).

Its flexibility is related to the type of information it can contain, as it can be expanded to include other PDP phases, such as post-processing schedules for AM technologies or assembly schedules. Including different PDP phases, the model can act as a boundary object between practitioners with different competences (Article C, Article D, Article F).

In conclusion, identification and modeling techniques for specification uncertainties are enhanced by their implementation in holistic modeling environments. Moreover, later PDP stages can be included in trade-off analysis during conceptual phases, through the identification and modeling of their respective engineering specifications (uncertain or not), thereby reducing the likelihood of unexpected redesign loops.

5.2.3. Summary

Section 5.3 aims at answering the following research question:

RQ3: How can uncertain engineering specifications be identified and modeled in a cost- and time-efficient way during the concept stage?

For a cost- and time-efficient identification and modeling of uncertain engineering specifications, this thesis proposes the implementation of a constraint replacement technique in a holistic modeling environment:

- Constraint replacement provides a systematic and guided procedure for identifying and gathering engineering specifications' unknown uncertainties.
- The proposed holistic modeling environment for the implementation of the constraints replacement technique is based on connecting product architecture FM models with PDP PERT activity models. This connection enables the inclusion of late PDP phases in engineering specification trade-off analysis, thus facilitating the identification of related uncertainties and the consequent design of more affordable products.

6

DISCUSSION

Technical and technological innovation through the implementation of new technologies is necessary for a reduction in cost and development times in the space industry (Cour des Comptes, 2019). However, as experienced during the research projects on which this thesis is based, gathering engineering specifications for designing with a new technology is hindered by the uncertainties regarding the technology's capabilities, what the technology can and cannot be used for, and the effect that the technology has on the overall PDP, especially the VVT phases, which tend to increase the cost of the PDP. These findings also align with literature by Roth et al. (2010), who state that historical data are often insufficient for the evaluation of new technologies. It was observed in these studies that the performance of past designs does not address the many sources of design uncertainty for new technologies, which in turn hinders the development of robust and accurate early cost and PDP schedule estimations. Similarly, Pettit (2003) states that design guidelines should promote the early recognition, characterization, and prioritization of sources of design uncertainty.

Along these lines, this thesis proposes the implementation of a holistic modeling environment or design platform to serve as a design support, based on FM techniques to model FRs, DSs and design constraints during conceptual stages. In the design platform, the FM is connected to a PERT diagram of the PDP downstream activities. The need for holistic modeling environments to ensure the development of high-performance, affordable space products is also highlighted by authors such as Staack et al. (2018) and Papageorgiou et al. (2020).

The main contribution of this modeling environment is the technique of design constraint modeling, classification, and replacement. Constraint modeling enables the acknowledgment and visualization of design constraints, aiding the designer in limiting the design space and designing products with feasible engineering specifications. In the literature, the importance of model visualization (Keim et al., 2008) and constraint modeling (Schmollgruber, 2018; Guan and Ghose, 2005) is well known and acknowledged; however, the process of systematic constraints replacement as proposed in this thesis is novel.

The proposed constraint modeling and replacement strategy supports the identification of UU design specifications, the documentation and evaluation of KUs, and their transformation into KKs. This transformation can be achieved using a combination of experts' assessments and test activities, which are strategies that the space industry is currently familiar with (Jensen et al., 2017; O´Brien, 2018; Dordlofva, 2020). However, the proposed holistic modeling environment takes the transformation of KUs into KKs one step further: By linking the FM with the PERT diagram, practitioners can evaluate not only what the most affordable way is to transform KUs into KKs but also whether this transformation is worthwhile.

Moreover, modeling the system architecture provides a concise way to capture the existing architecture and design requirements, which can facilitate system maintenance and improvement (NRC, 2010; Brice, 2011; Haskins et al., 2015; Karlow Herzog, 2018; Mokhtarian et al., 2019).

In this thesis, the types of uncertainties that were identified as the most problematic are those that are unknown (i.e., UUs), since practitioners do not know where to look to find them (Sutcliffe and Sawyer, 2013; Ramasesh and Browning, 2014; Jensen et al., 2017). The main consequence of UUs is the tendency among designers to design products with similar features to their predecessors, since the unknown data gap about the new technologies is filled with knowledge carried over from previous design projects, as stated by authors such as Kumke et al. (2016) and Seepersad et al. (2017). This "assumption" that the new design behaves in the same way as the old design presents a risk for budget and schedule overruns, as it is a source of unexpected surprises later in the PDP when design changes are more expensive and time consuming. Authors such as Chapman and Ward (2003) and Hubbard (2020) state that neglecting the identification of UUs leads to the establishment of non-adequate budget and schedule contingencies.

Modeling constraints in the FM enables the process of constraints replacement, where information pertaining to legacy technologies is analyzed to assess its relevance in the context of the new technology. This process has proven to be successful for identifying UUs and preventing the unintended knowledge carried over from previous products.

However, some UUs cannot be elicited from the constraints replacement process. As Roth et al. (2010) found, data about previous technologies are sometimes insufficient for the evaluation and estimation of new technologies. For this reason, the engineering specifications from traditional technologies might not provide a complete starting point to obtain new technology specifications through the constraints replacement process.

This fact is also related to the details that are deliberately included in and omitted from the FM. UUs about technology-related engineering specifications are discovered if their traditional technology counterpart is sufficiently modeled in terms of the model's depth, breadth, and fidelity (Haskins et al., 2015).

Moreover, many UUs that are uncovered through the constraints replacement technique (or any other technique) are not truly UUs, but rather aspects of the design, manufacturing, or testing process that escape the minds of practitioners during design stages. However, a relevant conclusion from the replacement technique is that the main objective in an organization must be the establishment of a culture of active "uncertainties seeking" to increase the probability of finding UUs during conceptual stages.

In this context, the implementation of a holistic multidisciplinary modeling approach is deemed necessary for ensuring model breadth and fidelity to support the identification of KUs and UUs (through constraint replacement) and their transformation into KKs.

In addition, another benefit of a holistic modeling environment is the inclusion of specifications pertaining to late PDP phases in the conceptual phases of engineering. This early inclusion enables the consideration of those later phases in design trade-off analysis. These observations resonate well with the work presented by authors such as Staack et al. (2018) and Papageorgiou et al. (2020), who propose the introduction of late PDP phases during conceptual stages to foster the design of better-performing systems and a more affordable PDP.

When considering the VVT activities during trade-off analysis in the conceptual stages, for example, it is possible to evaluate the additional testing costs and times required to improve a product model, compared to the benefits of the additional data they provide. This evaluation is highly dependent on the designers´ previous experience with a technology. As the technology is developed and knowledge about it increases, the models can change and improve. This feature aligns well with the work by NRC (2010) that states that a model-based design should not be a collection of static processes and models. Adaptable models enable adaptable testing strategies depending on technology novelty, product complexity, and PDP cost and schedule targets.

The suggestion that expensive and extensive test campaigns are not always necessary, combined with the targeted test campaigns that have been proposed in this thesis, highlights the possibility of a PDP where a new technology can be implemented radically, coupled with a strategy of marginal but targeted test campaigns (a fourth alternative to the three mentioned in Section 5.2), thereby reaping the benefits of a new technology without major detriments to the cost or development schedule.

Moreover, the inclusion of risk analysis directly in the FM and PERT diagrams, as proposed in this thesis, opens the possibility of discussing the partial completion or even elimination of low-risk VVT to cater to the needs of more modern and low-cost space PDPs.

This type of analysis, which considers partially performing or simply eliminating validation activities to reduce times and costs, enables design strategies such as those adopted by some NewSpace companies. One example is the development of mega constellations of satellites. In the past, satellites were developed as single units, and their manufacturing process involved long development and qualification phases to achieve high robustness and reliability to ensure around 15 years of useful operational life (Öhrwall Rönnbäck and Isaksson, 2018). With the mega satellite constellations proposed by NewSpace companies such as OneWeb (McDowell, 2020), reliability and robustness are not ensured at the level of an individual satellite (shortened development and qualification phases), but at a constellation level (Öhrwall Rönnbäck and Isaksson, 2018).

Product architecture and schedule models, uncertainty modeling, and risk assessment are all needed to develop an uncertainty-aware design and certification process.

However, as industrial participants stated in Article F, this is a multi-faceted issue, and the eventual design and test schedule of choice must reflect several competing factors that are outside of the scope of this thesis and proposed design platform. Some of these factors are the mindset of certification officials and decision makers, legal considerations and the overall perception of risk, and design and testing process costs.

Similar factors of influence can be found in the work by Pettit (2003) and in popular SE holistic design platforms such as those proposed by Blair and Love (2003), Robinson (2011), and El Souri et al., (2019). These platforms sustain the convenience of multidisciplinary model-based design frameworks for designing successful space products, yet do not include techniques (such as constraints replacements) to actively identify UUs. Moreover, being based on SE, these platforms present a common drawback identified in the SE discipline, as the explorative and iterative nature of the design process is generally disregarded. For this reason, these approaches tend to lack a formal theoretical strategy to address uncertainties and design exploration and to decrease the number of redesign loops to prevent time and cost overruns. Reducing redesign efforts to prevent such overruns is the objective of ED approaches (Suh, 1998), and SED is the discipline that aims at embedding the analysis of iterative ED efforts from ED into holistic multidisciplinary SE frameworks (Isaksson et al., 2017).

The constraints replacement technique and the connection between the FM and the PERT diagrams with the purpose of identifying UUs are grounded in SED principles and have the potential to bridge the gap between SE and ED disciplines. Based on ED principles, the proposed platform and methods strive for a systematic design uncertainty identification and a design exploration to reduce redesign loops, moreover, they can be used as a knowledge-transfer tool among practitioners. At the same time, they include the holistic, multidisciplinary and scalable nature of SE frameworks and their focus on the technical feasibility, requirements, and VVT phases.

7

RESEARCH VALIDATION

Validation refers to the scientific rigor of research (Le Dain et al., 2013; Isaksson et al., 2020). Validation activities are related to and sometimes mistaken for verification activities. According to Haskins et al. (2015) and ISO (2020), verification activities are carried out to confirm that the established requirements for a system's intended use have been fulfilled (i.e., verification activities ensure that the system is built right). In contrast, validation activities are performed to confirm that the system, its elements, and its products will achieve their intended use in the intended operational environment (i.e., validation activities ensure that the right system is built). Validation in research intends to answer the question, "Did you do the right research?" (Le Dain et al., 2013).

In research studies, hypotheses and results must be validated (Robson, 2002). However, as authors such as Popper (2002) state, hypotheses cannot be tested, only falsified. If repeated attempts at falsifying a hypothesis fail, then the probability of its verisimilitude increases. This was the strategy followed during the validation procedures for this thesis.

There are different approaches to validation in research; Isaksson et al. (2020) have presented a summary of some of them. Several approaches (Guba and Lincoln, 1989; Buur, 1990; Eckert et al., 2003; Le Dain et al., 2013) point to validating the research problem and its understanding separately from the approach to address it. This was the approach followed in this thesis.

7.1. Research gap validity

7.1.1. Validating the academic problem

Research should investigate and address valid problems (Le Dain et al., 2013). The academic problem addressed in this thesis (research gap) is the lack of a digital product design platform and respective design methods that are able to support the systematic identification and modeling of design unknowns during conceptual stages, when introducing a new technology. Failing to address uncertainties during conceptual stages leads to problems encountered during later PDP activities, where design and process changes are the most expensive and time consuming. The relevance of this research gap is also highlighted by other authors, such as Ramasesh and Browning (2014) and Browning and Ramasesh (2015), who state the need for a conceptual framework for identifying uncertainties during PDP; Hwang et al. (2019) and Stock et al. (2021), who suggest the need for a model framework where knowledge can be easily transferred and documented to facilitate early uncertainty identification; and Macedo et al.

(2019) and Bianchi et al. (2021), who advocate for a model to appropriately represent information (or the lack thereof) to foster creative solutions.

7.1.2. Validating the industrial problem

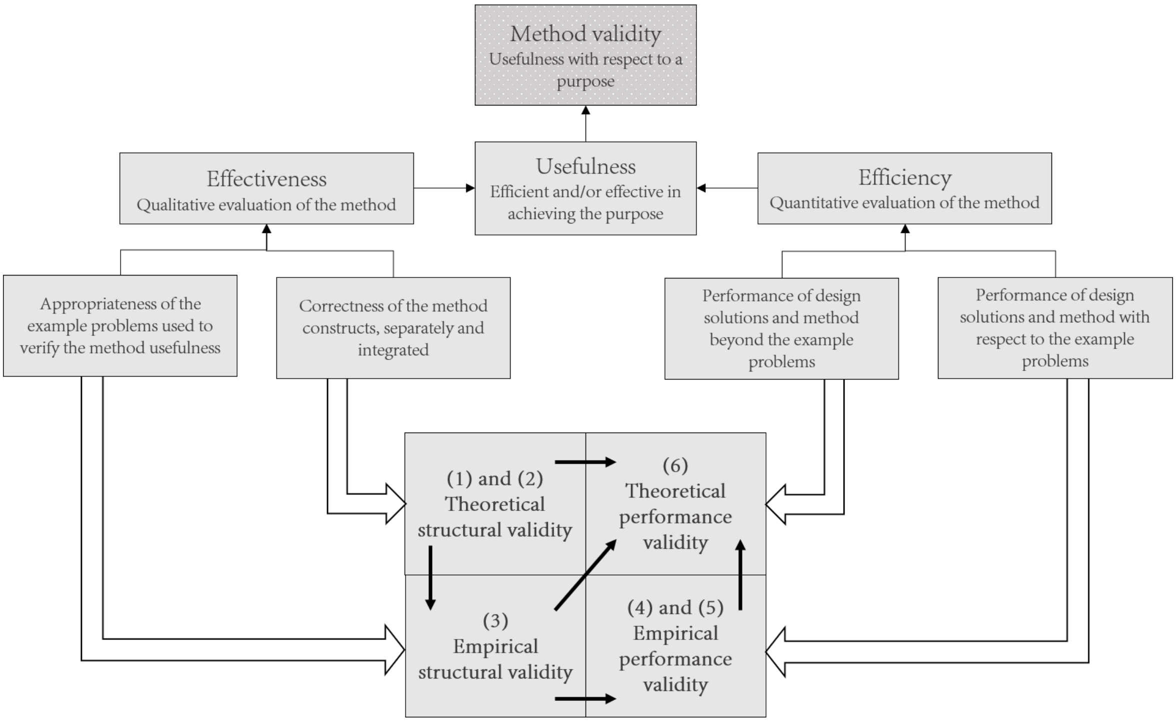
The industrial problem identified in this thesis is the lack of strategies for identifying known and unknown uncertainties during conceptual stages of the space PD.

During the conceptual stages of a PD process, needs and requirements are identified, refined, and compiled into requirements specifications, from which the product is then designed. However, the requirement-gathering activities for new technologies are hindered by a lack of knowledge regarding technology feasibility and the way in which technology introduction affects the whole PDP, especially the VVT phases. This gap is mentioned by authors such as Veritas (2001), Brice (2011), Dordlofva (2020), and Echsel et al. (2020), who are concerned with how the uncertainties related to technology feasibility affect product design. Other authors, such as Lord et al. (2018), the European Commission (2019), and Dordlofva (2020), have expressed their concerns related to the way in which uncertainties affect not only the product design but also the respective VVT activities.

Moreover, this industrial problem was also observed during the research projects (carried out with industrial practitioners) on which this thesis is based. The main articles in this thesis (Articles A to F) are all based on studies performed with industrial practitioners, where this industrial problem was a recurring topic. Articles A and B mention the uncertainties regarding DfAM in the space industry and the impact on qualification activities, as identified during the RIQAM project. Article C focuses on the design and manufacturing uncertainties encountered during RIQAM when designing for AM and the way in which these uncertainties can be addressed through targeted test activities, thereby reducing failure rates during later qualification. Articles D and E focus on addressing the qualification uncertainties faced during the CHEOPS project when introducing new technologies to the design of EPSs. Article F evaluates the usefulness of a digital platform for the identification of manufacturing and test uncertainties in the context of the DIDAM project.

7.2. Design method validity

The process of validating a design method involves demonstrating the usefulness of the design with respect to its intended purpose (Pedersen et al., 2000). Usefulness is evaluated through effectiveness; the method efficiently provides the correct DSs. In this context, a correct DS has an acceptable performance and is developed with less cost and time (Pedersen et al., 2000; Seepersad et al., 2006). To demonstrate the usefulness of the design method proposed in this thesis, the validation square was applied, as illustrated in Figure 7.1 (Pedersen et al., 2000; Seepersad et al., 2006).



7.1. Validation square methodology followed for validating the results presented in this thesis (Pedersen et al., 2000).

7.2.1 Theoretical and structural validity

Accepting the construct validity

Accepting the construct validity is related to demonstrating the validity of all the different pieces used to conform the proposed model or method.

The design platform proposed in this thesis is based on the implementation of four building blocks, which are well known and well established in literature and industry:

- Function models: FM techniques are well-established model-based tools in the ED and SE community (Eisenbart et al., 2012; Haskins et al., 2015). Multiple FM representations have been developed over the years (Weilkiens, 2007; Umeda et al., 1990; Heller and Feldhusen, 2013). In this thesis, the preferred FM technique is the EF-M technique, which has been developed in the ED community, has been used for over 20 years and is among the more industrially tested FM frameworks (Malmqvist, 1997; Müller et al., 2020).
- DSM: The first use of DSMs can be tracked to the 60s (Steward, 1962). In the 80s, their popularity increased when researchers at MIT and NASA began to apply them and extend their application and methods (Rogers, 1989; Black et al., 1990). Today, more than 3,000 articles reference the use and benefits of DSMs (Browning, 2015).
- Activity duration and cost models: The activity duration and cost models implemented in this thesis are based on the identification and quantification of duration and cost drivers, which can be tracked to the 80s (Shank, 1989). Since then, activity duration and cost models based on drivers have been common practice in PDPs (Ben-Arieh and Qian, 2003; Shabi et al., 2017; Tahera et al., 2019).
- PERT diagrams and critical path calculations: The PERT technique is a statistical tool popular in the project management literature, and it can be traced back to Malcolm et al. (1959). Its use, complemented with critical path calculations, can also be tracked to

the 50s. PERT diagrams and critical path calculations are still regarded as the cornerstones of project management (Ulusoy, 2021).

Accepting method consistency

Accepting method consistency is related to building confidence in the way the constructs work together. For this purpose, authors recommend the use of flow charts (Pedersen et al., 2000), such as the one presented in Figure 7.2 for evaluation of the consistency of the method proposed in this thesis. The information flow presented in Figure 7.2 suggests that the information generated from each construct is adequate and necessary for interaction with the other constructs.

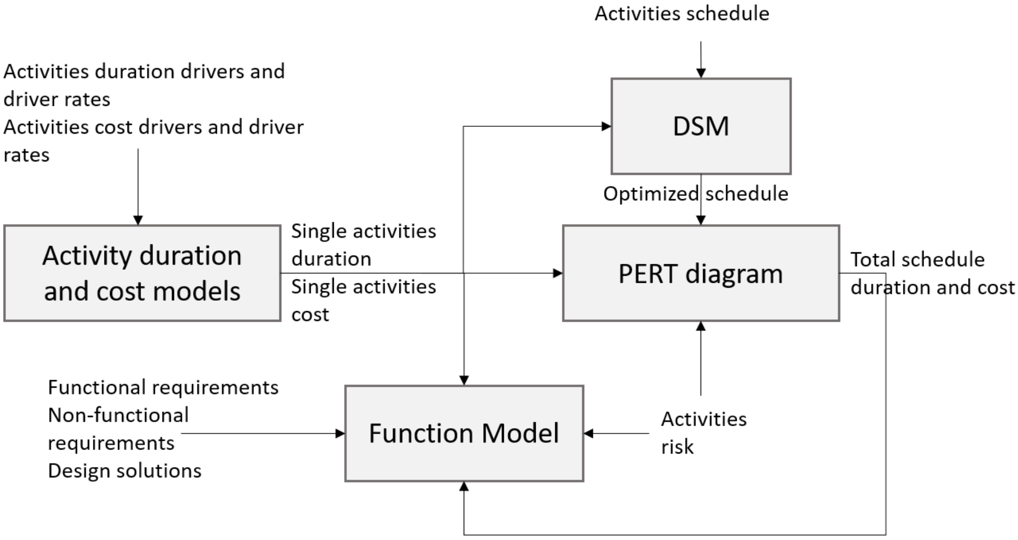


Figure 7.2 Constructs' information flow to ensure method consistency

Accepting both construct validity and method consistency can also be interpreted as "being logical." According to Olewnik and Lewis (2005), being logical is the first requirement for a decision support tool (the proposed digital design platform) to be valid. Moreover, the step of accepting method consistency through an information flow suggests that the method and design platform use meaningful and reliable information, which is the second requirement for the validation of decision support tools (Olewnik and Lewis, 2005). Meaningful information indicates that insights into the interdependencies of constructs are provided and make sense. As the design platform is meant to be used by industrial practitioners during conceptual phases of the PDP, it can be established that the information that will enter the platform is reliable (i.e., it comes from appropriate sources).

7.2.2. Empirical structural validity: Accepting the example problems

In this instance, confidence must be built on the appropriateness of the example problems chosen to verify the proposed method. Authors (Pedersen et al., 2000) suggest (1) proving that the example problems are similar to the problems for which the method constructs are accepted and (2) proving that the example problems are representative of the problems the method is supposed to address.

The evaluation of the method's usefulness was performed in Article F, using two case studies presented in Figure 7.3. These case studies featured the analysis of a flow connector and a heat exchanger for satellite applications redesigned for AM. In both cases, participants were instructed to identify manufacturing and test-related concerns as a way of identifying uncertainty in early conceptual stages. Both case studies are similar to the problems for which

the method constructs (FM, DSM, PERT diagram, and activity duration and cost models) are accepted. Functions models, and more specifically, EF-M techniques, have been widely used before in literature for the representation and assessment of space products (Muller et al., 2020). The same can be affirmed for PERT diagrams (Nagarajah, 2000; Skobelev et al., 2018), activity duration and cost models (Haedicke and Feil, 1991; Ben-Arieh and Qian, 2003), and DSMs (Rogers, 1989; Black et al., 1990).
The method was developed to support the design of space components through the early identification of product design and process uncertainties. As both the flow connector and the heat exchanger are products usually found in space systems, it can be stated that the example problems are representative of the problems the method is supposed to address.

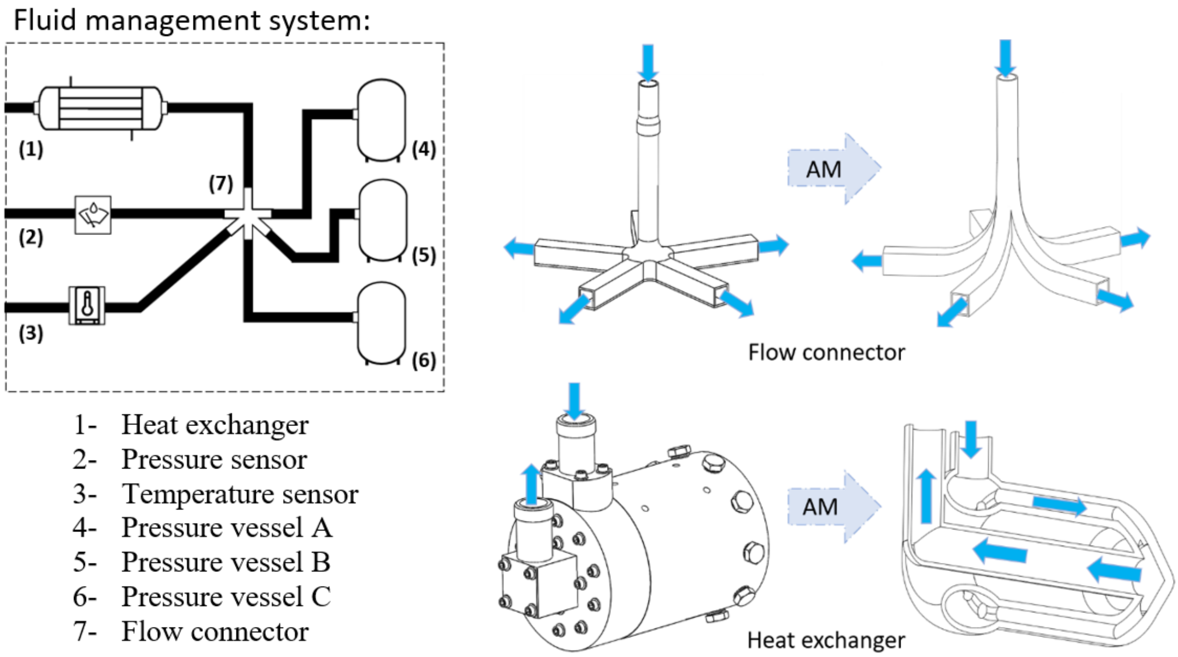


Figure 7.3. Case studies from Article F (extracted from Article F).

7.2.3 Empirical performance validity: Accepting the usefulness of the method for some example problems

To accept the usefulness of the method, authors (Pedersen et al., 2000) suggest applying the method to solve representative example problems. Then, usefulness must be proved to be linked to the method application.
Metrics for usefulness are related to the degree to which a purpose has been achieved. From the industrial perspective, the method’s purpose is the development of a method and design platform for supporting the identification of known and unknown uncertainties during the conceptual stages of the space PD, which in the long term would contribute to cost and development time reductions while ensuring high product quality. From an academic perspective, the purpose is related to the development of design methods and lessons learned, thus enabling the method to support the systematic identification and modeling of design unknowns during conceptual stages when introducing a new technology.
To accept the usefulness of the method for example problems and to accept that usefulness is linked to the method application, in Article F, the Solomon four-group experiment design (Sawilowsky et al., 1994; Mai et al., 2020; Trochim, 2021) was preferred.

The study involved 12 experienced industrial practitioners and featured the assessment of the DfAM of two satellite components. The results of the study suggest that the proposed platform and associated design methods are useful for identifying uncertainties and for proposing measures to address them. Moreover, the results indicate the need to make “uncertainties seeking” a common practice.

Regarding empirical performance validity, Olewnik and Lewis (2005) state that the third requirement (the first two were addressed in Section 7.2.1) for validating decision support tools, such as the proposed digital design platform, is assessing whether the tool biases the designer. This requirement relates to forcing preferences on the designer; in other words, the decision-making tool influences the outcome Saari (2000). In this regard, the abstract nature of the models used in the design platform prevents designer bias, as designers can build the model to fit their preferences. Moreover, the method constructs are flexible enough to enable the model’s evolution over time, which is necessary as companies constantly change their technology portfolios to remain competitive.

7.2.4 Theoretical performance validity: Accepting the usefulness of the method beyond example problems

To accept the usefulness of the method beyond the example problems, authors (Pedersen et al., 2000) suggest building confidence in the method’s generalizability. They state that if the method is proved to be useful for some limited instances, then it can be stated that the method is empirically performance valid (as established in Section 7.2.3). Thereafter, if the method is deemed useful beyond the example problems, then it can be considered to be theoretically performance valid.

To accept the usefulness of the method, the Solomon four-group experiment design was preferred. However, due to the small sample size (12 participants) and the artificial design setting in which the study was conducted (moderated, 20-minute design sessions with two participants), these results cannot be generalized. For this reason, the proposed method cannot be considered theoretically performance valid. Nevertheless, the results were still encouraging and motivated the development of a standalone digital application where the proposed design platform (based on the proposed methods) can be industrialized and implemented during conceptual phases in real design case scenarios.

Moreover, authors such as Ellis and Dix (2006) state that a large proportion of the design research methods and tools proposed in the literature are conducted in artificial settings and with small sample sizes, thus rendering them non-theoretically performance valid. However, their results are still useful for industry and academia.

8

CONCLUSION

When introducing new technologies in space products, the uncertainty regarding technology capabilities and the way in which the technology affects the PDP, especially in relation to V&V activities, hinders the early establishment of appropriate engineering specifications in conceptual stages. Some of the uncertainties found at this stage are known (i.e., they are KUs), and some are unknown (i.e., they are UUs).

KUs can be transformed into KKs through test campaigns or experts' assessments. However, UUs are problematic, since practitioners are not aware of them, and this lack of awareness can lead to unexpected problems arising during later PDP phases, where design and process changes are the most expensive.

In this thesis, a model-based method is proposed for the cost- and time-efficient identification and modeling of UUs and KUs when designing space products with new technologies.

The method is based on FM strategies for modeling product architecture and engineering specifications during conceptual design phases. These strategies enable the assessment and modeling of KUs and the identification of UUs through a process of systematic constraints replacement, where information pertaining to previous technologies is systematically analyzed to assess its relevance in the context of the new technology.

The function model is connected to the PERT diagrams of later PDP activities and aims at evaluating the impact that design changes have on the overall PDP schedule. The holistic modeling environment (or digital platform) that results from the connection between FM and PERT diagrams supports the development of cost- and time-efficient strategies to gather information to reduce uncertainties and establish engineering specifications for the new technology. Apart from the holistic modeling environment, results highlight the need to establish a culture of "uncertainty seeking" during early PDP phases to facilitate technology introduction.

As with conventional ED methods, the proposed modeling environment and methods aim for a systematic uncertainty identification and design exploration to reduce redesign loops. At the same time, they are compatible with the holistic and multidisciplinary nature of SE frameworks and their focus on the technical feasibility and requirements as well as VVT phases.

In conclusion, the proposed platform and methods are grounded in the principles of the SED discipline and have the potential to bridge the gap between the SE discipline, mostly implemented in industry, and the academic ED disciplines.

The proposed methods were validated by assessing their usefulness in their intended operational context. The validation process was performed through the assessment of theoretical and empirical structural validity and the assessment of theoretical and empirical performance validity. However, due to the small sample size and the artificial design setting in which performance validity was evaluated, the results cannot be generalized, and the method is deemed useful only for some limited instances. The method is hence empirically performance valid, but not theoretically performance valid. However, a large proportion of the design research methods are not theoretically valid, and their results are still useful for industry and academia.

8.1. Future work

Through an application research-based validation grant awarded by the Innovation office at Chalmers University of Technology, the methods and digital platform proposed in this thesis were developed as a stand-alone digital design platform in the DEBAS project, which took place during the last months of these PhD studies. The objective of the DEBAS project was to develop a minimum viable product that could be tested by practitioners in real industrial settings, to evaluate future commercial applications of this thesis. This digital product intends to evaluate the method's usefulness in unmoderated real design scenarios through the access to larger sample sizes enables by a stand-alone application. The DEBAS platform is still under development, and industrial testing is pending.

Other future improvements include the addition of different PDP activities to the PERT diagram included in the platform; the inclusion of different types of constraints in the FM; and the connection of the proposed design platform with other PDP assessment tools, such as value creation strategy models or geometry representations currently under development by the SED group at Chalmers University of Technology.

REFERENCES

Andersen A. (2006). Well Technology Qualification. Expro-soft Technical report, Trondheim, Norway.

Barn B., Barat S. and Clark T. (2017). Conducting Systematic Literature Reviews and Systematic Mapping Studies, Proceeding ISEC '17 /10th Innovations in Software Engineering Conference, Jaipur, India, ACM New York, NY, USA © 2017, pp. 212-213. Doi: 10.1145/3021460.3021489.

Bell E., Bryman A. and Harley B. (2018). Business research methods. Oxford university press.

Ben-Arieh, D., and L. Qian. (2003). Activity-based cost management for design and development stage. International Journal of Production Economics 83(2): 169-183.

Bianchi D., Amadori K., Bäckström E., Jouannet C., and Secco N. (2021). An Uncertainty-based Framework for Technology Portfolio Selection for Future Aircraft Program. In AIAA Scitech 2021 Forum, pp. 1479.

Biliyard B. (2018). Aerospace castings, NASA. NASA Marshall Space Flight Center; Huntsville, AL, United States Retrieved from: https://ntrs.nasa.gov/search.jsp?R=20170012457.

Black T.A., Fine C.F., and Sachs E.M. (1990). A Method for Systems Design Using Precedence Relationships: An Application to Automotive Brake Systems, MIT Sloan School of Management, Cambridge, MA, Working Paper no. 3208.

Blair M., and Love M. (2003). Scenario-Based Affordability Assessment Tool. AIR FORCE RESEARCH LAB WRIGHT-PATTERSON AFB OH.

Blessing L.T., and Chakrabarti A. (2009) DRM: A Design Reseach Methodology, pp. 13-42. Springer London.

Borgovini R., Pemberton S., and Rossi M. (1993). Failure mode, effects, and criticality analysis (FMECA), RELIABILITY ANALYSIS CENTER GRIFFISS AFB NY.

Boyard N. (2015). Méthodologie de conception pour la réalisation de pièces en Fabrication Additive (doctoral dissertation). l'École Nationale Supérieure d'Arts et Métiers Spécialité " Génie mécanique - procédés de fabrication", Paris, France.

Brice C.A. (2011). Unintended consequences: How qualification constrains innovation, In Proceedings of the 1st World Congress on Integrated Computational 735 Materials Engineering (ICME), John Wiley and Sons, pp. 241, https://doi.org/10.1002/9781118147726.ch34.

Browning T.R. (2015). Design structure matrix extensions and innovations: a survey and new opportunities. IEEE Transactions on Engineering Management, 63(1): pp. 27-52.

Buede D.M. and Miller W.D. (2016). The engineering design of systems: models and methods. John Wiley & Sons.

Buur J. (1990). A Theoretical Approach to Mechatronics Design, (doctoral dissertation), Institute for Engineering Design, Technical University of Denmark, Lyngby, Denmark.

Chakrabarti A., and Blessing L.T. (2014). Theories and models of design: A summary of findings. In An anthology of theories and models of design, pp. 1-45. Springer, London.

CHEOPS (2020). Consortium for Hall Effect Orbital Propulsion System, The future of electric propulsion for in-space operation and transportation. https://www.cheops-h2020.eu/

Chang Y-K., Hwang K-L., and Kang S-J. (2007). SEDT (System Engineering Design Tool) development and its application to small satellite conceptual design. Acta Astronautica, 61(7-8): pp. 676-90.

Chapman C., and Ward S. (1996). Project risk management: processes, techniques and insights. John Wiley.

Chen M., Ebert D., Hagen H., Laramee R. S., Van Liere R., Ma K. L., ... and Silver D. (2008). Data, information, and knowledge in visualization. IEEE computer graphics and applications, 29(1): pp. 12-19.

Chechile I. (2021). The Hitchhiker's Guide to NewSpace. In NewSpace Systems Engineering, pp. 1-34. Springer, Cham.

Claesson A. (2006). A configurable component framework supporting platform-based product development (doctoral dissertation). Chalmers University of Technology, Gothenburg, Sweden.

Cour des Comptes (2019). Le rapport public annuel 2019 - La politique des lanceurs spatiaux: d'importants défis à relever. www.ccomptes.fr.

Cross N. (2001). Designerly ways of knowing: Design discipline versus design science. Design issues, 17(3), pp. 49-55.

Dordlofva C. and Törlind P. (2018). Design for Qualification: A Process for Developing Additive Manufacturing Components for Critical Systems. In NordDesign 2018.

Dordlofva C. (2020). A Design for Qualification Framework for the Development of Additive Manufacturing Components—A Case Study from the Space Industry. Aerospace, 7(3), pp. 25.

Echsel M., Springer P., and Hümbert S. (2020). Production and planned in-orbit qualification of a function-integrated, additive manufactured satellite sandwich structure with embedded automotive electronics. CEAS Space Journal.

Eckert C.M., Clarkson P.J., and Stacey M.K. (2003). The Spiral of Applied Research: A Methodological View on Integrated Design Research, ICED03: 14th International Conference on Engineering Design.

Eisenbart B., Gericke K. and Blessing, L. (2012). A shared basis for functional modelling. In DS 71: Proceedings of NordDesign 2012, the 9th NordDesign conference, Aarlborg University, Denmark. 22-24.08. 2012. ISBN: 978-87-91831-51-5.

El Souri M., Gao J., and Simmonds C. (2019). Integrating Manufacturing Knowledge with Design Process to Improve Quality in the Aerospace Industry. Procedia CIRP, 84: pp. 374-379.

Ellis G., and Dix A. (2006). An explorative analysis of user evaluation studies in information visualisation. In Proceedings of the 2006 AVI workshop on Beyond time and errors: novel evaluation methods for information visualization, pp. 1-7. ACM, Venice, Italy.

Engel A., and Barad M. (2003). A methodology for modeling VVT risks and costs. Systems engineering 6(3): pp. 135-151.

Engel A. (2010). Verification, Validation, and Testing of Engineered Systems. Wiley, Hoboken, NJ.

Eppinger S., and Ulrich K. (2015). Product design and development. McGraw-Hill Higher Education.

Erden M.S., Komoto H., van Beek T.J., D'Amelio V., Echavarria E. and Tomiyama T. (2008). A review of function modelling: Approaches and applications. Ai Edam, 22(2), pp. 147-169.

ESA (2019). Ariane 5. ESA, accessed July 01, 2019, https://www.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_5

European commission (2019). The future of the European space sector: How to leverage Europe's technological leadership and boost investments for space ventures

Furtado S., Hamedifar H., Mateen K., Huyse L., Rivero L. M., and Kusinski G. (2016). Development of Novel Integrity Assurance Approach for Technology Qualification of New Subsea Technologies by Deepstar®. In Offshore Technology Conference. Offshore Technology Conference.

Gero J.S. (1990). Design prototypes: A knowledge representation schema for design. AI Magazine 11(4): pp. 26–36

Gero J. S., and Kannengiesser U. (2007). A function–behavior–structure ontology of processes. Ai Edam, 21(4): pp. 379-391.

GKN (2019). About GKN Aerospace in Sweden. GKN Aerospace. Accessed in July 29: https://www.gknaerospace.com/en/about-gkn-aerospace/locations/gkn-aerospace-in-europe/gkn-aerospace-in-sweden/

Grady J.O. (2006). System Requirements Analysis. Elsevier Academic Press, Amsterdam.

Greene M., Gonzalez R., Papalambros P., and McGowan A.M. (2017). Engineering design: What's the difference?. In DS 87-2 Proceedings of the 21st International Conference on Engineering Design (ICED 17) 2: Design Processes, Design Organisation and Management, Vancouver, Canada, 21-25.08. 2017: pp. 467-476.

Goldberg C., Nalianda D., Sethi V., Pilidis P., Singh R., and Kyprianidis, K. (2018). Assessment of an energy-efficient aircraft concept from a techno-economic perspective. Applied Energy, 221: pp. 229-238.

Guan Ying, and Ghose A.K. (2005). Use constraint hierarchy for non-functional requirements analysis. International Conference on Web Engineering. Springer, Berlin, Heidelberg.

Guba E.G. and Lincoln Y.S. (1989). Fourth Generation Evaluation, Sage Publications, Newbury Park, CA, USA.

Haik Y., Sivaloganathan S., and Shahin T. M. (2015). Engineering design process. Cengage Learning.

Hatchuel A., and Weil B. (2009). CK design theory: an advanced formulation. Research in engineering design, 19(4): pp. 181.

Hirtz J., Stone R.B., McAdams D.A., Szykman S., and Wood K.L. (2002). A functional basis for engineering design: reconciling and evolving previous efforts. Research in engineering Design, 13(2): pp. 65-82.

Hwang S., Kim H., Hur D., and Schoenherr T. (2019). Interorganizational information processing and the contingency effects of buyer-incurred uncertainty in a supplier's component development project. International Journal of Production Economics, 210: pp. 169-183.

Kitchenham B. and Charters S. (2007). Guidelines for performing systematic literature reviews in software engineering, Keele University, Durham, UK.

Haedicke J., and Feil D. (1991). In a DOD Environment: Hughes Aircraft Sets the Standard for. Strategic Finance, 72(8): pp. 29.

Haskins C., Forsberg K., Krueger M., Walden D., and Hamelin D. (2015). Systems engineering handbook. In INCOSE.

Heller J. and, Feldhusen J. (2013). Enhanced function structure applicability through adaptive function templates. Athens: ATINER´S Conference paper series, No: IND2013-0743.

Henry C. (2016). Next Space Edition 2016 - Six Investor Expectations for the NewSpace Sector, Via Satellite, accessed September 17, 2018, http://interactive.satellitetoday.com/via/nextspace-edition-2016/six-investorexpectations-for-the-newspace-sector/.

Hiriart T. and Saleh J. (2010). Observations on the Evolution of Satellite Launch Volume and Cyclicality in the Space Industry, Space Policy, 26: pp. 53-60.

Hobday M. (1998). Product Complexity, Innovation, and Industrial Organization, Research Policy, 26: pp. 689-710.

Hubbard D.W. (2020). The failure of risk management: Why it's broken and how to fix it. John Wiley & Sons.

Isaksson O., Arnarsson Í., Bergsjö D., Catic A., Gustafsson G., Kaya O., ... and Ström M. (2017). Trends, observations and drivers for change in systems engineering design. In DS 87-3 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 3: Product, Services and Systems Design, Vancouver, Canada, 21-25.08. 2017, pp. 201-210.

Isaksson O., C. Eckert, M. Panarotto, and J. Malmqvist. (2020). You Need To Focus ToValidate. Proceedings of the Design Society: DESIGN Conference, 1: pp. 31–40. doi: 10.1017/dsd.2020.116.

ISO/IEC/IEEE (2020). ISO/IEC/IEEE 12207-2:2020(E), Systems and Software Engineering—Software Life Cycle Processes, Part 2: Relation and Mapping Between ISO/ IEC/IEEE 12207:2017 and ISO/IEC. 12207:2008, 4–27. Vernier, Geneva: ISO/IEC/IEEE.

Kunskapsformedlingen (2019). Infrastructure for Digitalization enabling industrialization of Additive manufacturinG (IDAG), Kunskapsformedlingen, accessed August 23, 2019, https://kunskapsformedlingen.se/projekt/infrastructure-for-digitalization-enabling-industrialization-of-additive-manufacturing-idag/.

Jensen M.B., Elverum C.W., and Steinert M. (2017). Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. Design Studies, 49: pp. 1-31.

Johannesson H. and Claesson A. (2005). Systematic product platform design: A combined function-means and parametric modelling approach. Journal of Engineering Design, 16(1): pp. 25–43. doi: https://doi.org/10.1080/09544820512331325247.

Karlow Herzog P. (2018). Surface characterization in Additive Manufacturing-An empirical study of angular dependency (Master´s degree thesis) Lund University, ID: 8963731.

Keim D., Andrienko G., Fekete J.D., Görg C., Kohlhammer J., and Melançon G. (2008). Visual analytics: Definition, process, and challenges. In Information visualization, pp. 154-175. Springer, Berlin, Heidelberg.

Krishnaswamy O.R. and Satyaprasad B.G. (2010). Business research methods. Himalaya Publishing House.

Kumke M., Watschke H. and Vietor T. (2016). A New Methodological Framework for Design for Additive Manufacturing. Virtual and Physical Prototyping 11 (1): pp. 3–19. Taylor & Francis Online doi: 10.1080/17452759.2016.1139377.

Lal B. (2016). Reshaping Space Policies to Meet Global Trends. Issues in Science and Technology 32 (4): pp. 63.

Le Dain M., Blanco E., and Summers J.D. (2013). Assessing design research quality: Investigating verification and validation criteria. Proceedings of the International Conference on Engineering Design, ICED, 2 DS75-02: pp. 183–192.

Lee J., Deng W-Y., Lee W-T., Lee S-J., Hsu K-H., and Ma S-P. (2010). Integrating process and work breakdown structure with design structure matrix. Journal of Advanced Computational Intelligence and Intelligent Informatics, 14 (5): pp. 512-522.

Lindwall A., Dordlofva C., and Öhrwall Rönnbäck A. (2017). Additive Manufacturing and the Product Development Process: insights from the space industry. In 21st International Conference on Engineering Design (ICED).

Lindwall A., and Törlind P. (2018). Evaluating Design Heuristics for Additive Manufacturing as an Explorative Workshop Method. In: Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia, pp. 1221-1232, doi: 10.21278/idc.2018.0310.

Loch C. and Kavadias S. (2008). Handbook of new product development management. Routledge.

Lord P.W., Tilley S., Goebel D.M., and Snyder J.S. (2018). Third generation commercial solar electric propulsion: A foundation for space exploration missions. In 2018 IEEE Aerospace Conference, pp. 1-15. IEEE.

Macedo K., Marinho M., and Santos S. (2019). Uncertainty Management in Software Projects: A Case Study in a Public Company. arXiv preprint arXiv:1902.05835.

Mai N.N., Takahashi Y., and Oo M.M. (2020). Testing the Effectiveness of Transfer Interventions Using Solomon Four-Group Designs. Education Sciences, 10(4): pp. 92.

Malcolm D.G., Roseboom J.H., Clark C.E., and Fazar W. (1959). Application of a technique for research and development program evaluation. Operations research, 7(5): pp. 646-669.

Malmqvist J. (1997). Improved function-means trees by inclusion of design history information, Journal of Engineering Design, 8 (2): pp. 107-117.

Martin G.L. (2014). NewSpace: The "emerging" commercial space industry. NASA Ames Research Center; Moffett Field, CA United States, ID: 20140011156.

McDowell J. C. (2020). The Low Earth Orbit Satellite Population and Impacts of the SpaceX Starlink Constellation. arXiv preprint arXiv:2003.07446.

Meisel N.A., Woods M.R., Simpson T.W., and Dickman C.J. (2017). Redesigning a Reaction Control Thruster for Metal-Based Additive Manufacturing: A Case Study in Design for Additive Manufacturing, Journal of Mechanical Design, 139(10), https://doi.org/ 10.1115/1.4037250.

Miles M.B. and Huberman A.M. (1994). Qualitative Data Analysis: An Expanded Sourcebook, Sage Publications, Beverly Hills, CA.

Miles M.B., Huberman A.M. and Saldana J. (2013). Fundamental of qualitative Data Analysis. In: Qualitative data analysis, pp. 69-105. London: Sage publications Ltd.

Mokhtarian H., Hamedi A., Nagarajan H.P., Panicker S., Coatanéa E., and Haapala K. (2019). Probabilistic Modelling of Defects in Additive Manufacturing: A Case Study in Powder Bed Fusion Technology, Procedia CIRP, 81: pp. 956-961, https://doi.org/10.1016/j.procir.2019.03.234.

Müller J.R., Siiskonen M.D.I., and Malmqvist J. (2020). Lessons learned from the application of enhanced Function-Means modelling. In Proceedings of the Design Society: DESIGN Conference, 1: pp. 1325-1334. Cambridge University Press.

Murthy P.D.N., Rausand M. and Østerås T. (2008). Product Reliability: Specification and Performance. Springer, London.

Nagarajah B. (2000). Designing risk-management strategies for GEO satellite telemetry, tracking and command ground systems. In 2000 IEEE Aerospace Conference. Proceedings (Cat. No. 00TH8484), 2: pp. 427-435. IEEE.

NASA (1970). Qualification testing. NASA Space vehicle design criteria, NASA SP-8044. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710019569.pdf

NATO AVT-092. (2009). Qualification by Analysis. Technical report. RTO-TR-AVT-092, North Atlantic Treaty Organization (NATO).

NRC (2010). Technologies and approaches to reducing the fuel consumption of medium-and heavy-duty vehicles. Appendix H- Model-Based Design, KEY ELEMENTS OF MODEL-BASED DESIGN, National Research Council National Academies Press.

O'Brien M.J. (2018). Development and qualification of additively manufactured parts for space, in Helvajian, H., Piqué, A. and Gu, B. (Eds.), Proceedings of SPIE, Laser 3D Manufacturing V, SPIE, pp. 1–14.

Ogaji S.O.T., Pilidis P., and Hales R. (2007). TERA-a tool for aero-engine modelling and management.

OHB (2019) We are OHB Sweden. Accessed in July 29: http://www.ohb-sweden.se/

Öhrwall Rönnbäck A.B., and Isaksson O. (2018). Product development challenges for space subsystems manufacturers, In: Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia. doi: https://doi.org/10.21278/idc.2018.0534.

Olewnik A.T., and Lewis K. (2005). On validating engineering design decision support tools. Concurrent Engineering, 13(2): pp. 111-122.

Pahl G.M Beitz W., Feldhusen J., and Grote, K. (2007). Engineering design: a systematic approach. London : Springer London : Imprint: Springer, 9781846283192.

Papageorgiou A., Ölvander J., Amadori K., and Jouannet C. (2020). Multidisciplinary and multifidelity framework for evaluating system-of-systems capabilities of unmanned aircraft. Journal of Aircraft, 57(2): pp. 317-332.

Pasquinelli M., Basso V., Mazzini S., Baracchi L., Puri S., Gerbaz D., and Viitaniemi J. (2014). Model-based approach for the verification enhancement across the lifecycle of a space system. In 6th International Conference on Systems and Concurrent Engineering for Space Applications.

Pecht M.G. (1993). Design for Qualification, In Proceedings of Annual Reliability and Maintainability Symposium, pp. 1–4, https://doi.org/ 10.1109/RAMS.1993.296885.

Pedersen K., Emblemsvag J., Bailey R., Allen J., and Mistree F. (2000). The'Validation Square'-Validating Design Methods. In ASME Design Theory and Methodology Conference. New York: ASME.

Pettit C.L. (2003). Uncertainty quantification for airframes: current status, needs, and suggested directions. SAE transactions, pp. 439-451

Popper K. (2002). The Logic of Scientific Discovery. Routledges Classics, London and New York. ISBN 0-203-99462-0.

Pradel P., Zhu Z., Bibb R. and Moultrie J. (2018). Investigation of design for additive manufacturing in professional design practice. Journal of Engineering Design, 29(4-5): pp. 165-200.

Prasad N. (2017). Traditional Space and NewSpace Industry in India- Current Outlook and Perspectives for the Future, pp. 11-22.

Preussger A., Kanert W., and Gerling W. (2003). Reliability qualification of a smart power technology for high temperature application based on physics-of-failure and risk and and opportunity assessment, In 2003 IEEE International Reliability Physics Symposium Proceedings, pp. 378–384, https://doi.org/10.1109/RELPHY.2003.1197777.

Qian Y., Lin J., Goh T.N., and Xie M. (2011). A novel approach to DSM-based activity sequencing problem. IEEE Transactions on Engineering Management 58 (4): pp. 688-705.

Qiao L, Ryan M. (2015). Applying the Design Structure Matrix (DSM) to SAR satellite formation flying design. Systems Engineering Test Evaluation Conference (SETE).

Raja V., and Isaksson O. (2015). Generic Functional Decomposition of an Integrated Jet Engine Mechanical Sub System Using a Configurable Component Approach. In ISPE CE, pp. 337-346.

Raju P., Thomas A.M., and Chapman C.B. (2012). The potential of knowledge-based engineering for space application design. In Proceedings of the 5th NASA/ESA International Workshop on Systems and Concurrent Engineering for Space Applications (SECESA 2012), Instituto Superior Técnico (IST), Lisbon, Portugal. European Space Agency, Noordwijk, The Netherlands.

Ramasesh R.V., and Browning T.R. (2014). A conceptual framework for tackling knowable unknown unknowns in project management. Journal of operations management, 32(4): pp. 190-204.

Rausand M.R.M. (2015). Technology qualification program integrated with product development process. International Journal of Performability Engineering, 11(1): pp. 3-1.

RISE (2020). DigiQUAM-Digital Platform for Additive Manufacturing. Retrieved from: https://www.ri.se/en/what-we-do/projects/digiquam-digital-platform-for-additive-manufacturing.

Robinson J. (2011). An overview of NASA's integrated design and engineering analysis (IDEA) environment. In 17th AIAA international space planes and hypersonic systems and technologies conference, pp. 2392.

Robson C. (2002). Real world research, Second Edition, Blackwell Publishing, Oxford.

Rogers J.L. (1989). A Knowledge-Based Tool for Multilevel Decomposition of a Complex Design Problem, NASA, Hampton, VA, Technical Paper TP-2903.

Roth G., Livingston J., Blair M., and Kolonay R. (2010). CREATE-AV DaVinci: computationally-based engineering for conceptual design. In 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, pp. 1232.

Rowell L.F., and Korte J.J. (2003). Launch vehicle design and optimization methods and priority for the advanced engineering environment.

Rymdstyrelsen (2019). Beviljade bidrag. Rymdstyrelsen, accessed August 16, 2019, https://www.rymdstyrelsen.se/innovation/beviljade-bidrag/

Saari D. (2000). Mathematical Structure of Voting Paradoxes. I; Pair-wise Vote. II; Postional Voting, Economic Theory, 15: pp. 1–103.
Salonitis K. (2016). Design for additive manufacturing based on the axiomatic design method. International Journal of Advanced Manufacturing Technology, 87(1–4): pp. 989–996. https://doi.org/10.1007/s00170-016-8540-5.
Sawilowsky S., Kelley D.L., Blair R.C., and Markman B.S. (1994). Meta-analysis and the Solomon four-group design. The Journal of Experimental Education, 62(4): pp. 361-376.
Schmollgruber P. (2018). Enhancement of the conceptual aircraft design process through certification constraints management and full mission simulations. Engineering Sciences. Doctorat de l'Université de Toulouse délivré par l'Institut Supérieur de l'Aéronautique et de l'Espace (ISAE).
Seepersad, C. C., Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J. K., and Mistree, F. (2006). The validation square: how does one verify and validate a design method. Decision making in engineering design, pp. 303-314.
Seepersad C.C., Allison J., and Sharpe C. (2017). The need for effective design guides in additive manufacturing. In DS 87-5 Proceedings of the 21st International Conference on Engineering Design (ICED 17) 5: Design for X, Design to X, Vancouver, Canada, 21-25.08. 2017: pp. 309-316.
Selding (2015). With Revenue Looking Up, Arianespace Seeks To Bring Ariane 5 Costs Down. Space News, accessed July 01, 2019, https://spacenews.com/with-revenue-looking-up-arianespace-seeks-to-bring-ariane-5-costs-down/
Shabi J., Reich Y., and Diamant R. (2017). Planning the verification, validation, and testing process: A case study demonstrating a decision support model, Journal of Engineering Design 28(3): pp. 171-204, https://doi.org/ 10.1080/09544828.2016.1274964.
Shafaat A., and Kenley C.R. (2015). Exploring the role of design in systems engineering. In INCOSE International Symposium, 25 (1): pp. 357-370.
Shalal (2019). Ariane 6 rockets sees fists commercial deals in race with SpaceX. Reuters, accessed July 01, 2019, https://www.reuters.com/article/us-arianegroup-contracts/ariane-6-rocket-sees-first-commercial-deals-in-race-with-spacex-idUSKCN1QA2BW
Shank J.K. (1989). Strategic Cost Management: New wine or just new bottles?. Journal of Management Accounting Research.
Skobelev P., Kozhevnikov S., Mayorov I., Poludov D., and Simonova E. (2018). Smart projects: Multi-agent solution for aerospace applications. International Journal of Design & Nature and Ecodynamics, 12(4): pp. 492-504.
Smith R.P., and Morrow J.A. (1999). Product development process modeling. Design studies, 20(3): pp. 237-261.
Smith H., Sziroczák D., Abbe G.E., and Okonkwo P. (2019). The GENUS aircraft conceptual design environment. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 233(8): pp. 2932-2947.
Staack I., Amadori K., and Jouannet C. (2018). A Holistic Engineering Approach for Aeronautical Product Development, 31st Congress of the International Council of the Aeronautical Sciences, International Council of the Aeronautical Sciences (ICAS), Bonn, Germany.
Stephenson W.J., Veley D.E., and Hill S. (2007). Composite Vehicle Design Environment, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, pp. 23.
Steward D.V. (1981). The Design Structure System: A Method for Managing the Design of Complex Systems. In: IEEE Transactions on Engineering Management. 28(3): pp. 71-74.
Steward D.V. (1962). On an Approach to Techniques for the Analysis of the Structure of Large Systems of Equations, SIAM Review, 4: pp. 321-342.

Stock G.N., Tsai J.C.A., Jiang J.J., and Klein G. (2021). Coping with uncertainty: Knowledge sharing in new product development projects. International Journal of Project Management, 39(1): pp. 59-70.

Struck C., and Hensen J. (2007). On supporting design decisions in conceptual design addressing specification uncertainties using performance simulation. In Proceedings of the 10th IBPSA Building Simulation Conference, pp. 3-5.

Suh N.P. (1990). The principles of design (No. 6). Oxford University Press on Demand.

Suh N.P. (1998). Axiomatic design theory for systems. Research in engineering design, 10(4): pp. 189-209.

Sutcliffe A., and Sawyer P. (2013). Requirements elicitation: Towards the unknown unknowns. In 2013 21st IEEE International Requirements Engineering Conference (RE), pp. 92-104. IEEE.

Tahera K., D.C. Wynn C. Earl and C.M. Eckert. (2019). Testing in the incremental design and development of complex products. Research in Engineering Design 30(2): pp. 291-316.

TechnoSoft (2021). Adaptive Modelling Language, TechnoSoft, Retrieved from: https://www.technosoft.com/application-software/adaptive-modeling-language/, Last accessed 2021/05/22,

Thomsen B., Kokkolaras M., Månsson T., and Isaksson O. (2017). Quantitative assessment of the impact of alternative manufacturing methods on aeroengine component lifing decisions, Journal of Mechanical Design, 139 (2), https://doi.org/10.1115/1.4034883.

Thompson M., Moroni G., Vaneker T., Fadel G., Campbell R., Gibson I., and Martina F. (2016). Design for additive manufacturing: Trends, opportunities, considerations, and constraints. CIRP Ann., 65: pp. 737–760, doi:10.1016/j.cirp.2016.05.004.

Tompkins Z., Grenn M., and Roberts B. (2020). Improving System Maturity Assessments by Incorporating a Design Structure Matrix. IEEE Transactions on Engineering Management, 67(1).

Trochim M.K. (2021). Experimental design. Retrieved from: https://conjointly.com/kb/experimental-design/

Ulusoy G. (2021). An Introduction to Project Modeling and Planning. Springer Nature.

Umeda Y., Takeda H., and Tomiyama T. (1990). Function, Behaviour and Structure. Applications of artificial intelligence in engineering, pp. 177–194. Berlin: Springer.

Veritas D.N. (2001). Qualification procedures for new technology. DNV RP-A203.

Vermaas P.E. (2013). The Co-Existence of Engineering Meanings of Function: Four Responses and Their Methodological Implications, Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27: pp. 191-202.

Wang W., Azarian M.H., and Pecht M. 2008. Qualification for Product Development. International Conference on Electronic Packaging Technology & High Density Packaging, Shanghai, China. IEEE.

Weilkiens T. (2007). Systems engineering with SysML/UML: Modeling, analysis, design. Amsterdam, Boston: Elsevier.

Whitney P. (2000). Tracing the Evolutionary Path for Space Technologies, Space Policy, 16: pp. 171-183.

Williamson K., and Bow A. (2002). Analysis of quantitative and qualitative data. K. Williamson, Research methods for students and professionals: Information management and systems, 2: pp. 285-303.

Wohlin C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering, Proceeding EASE '14 Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering, London, England, United Kingdom, ACM New York, NY, USA ©2014. doi: 10.1145/2601248.2601268

Wynn D.C., and Clarkson P.J. (2018). Process models in design and development. Research in Engineering Design 29 (2): pp. 161-202.

Yadav O.P., Singh N., and Goel P.S. (2006). Reliability demonstration test planning: A three dimensional consideration, Reliability Engineering and System Safety, 91(8): pp. 882–893, https://doi.org/10.1016/j.ress.2005.09.001

Article A

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018
https://doi.org/10.21278/idc.2018.0412

IMPACT ON DESIGN WHEN INTRODUCING ADDITIVE MANUFACTURING IN SPACE APPLICATIONS

O. Borgue, M. Panarotto and O. Isaksson

Abstract
This paper studied how the introduction of additive manufacturing (AM) in space applications impacts the design phases. Together with three manufacturers of space applications, the potential benefit as well as constraints are studied to identify design gaps. A literature survey is conducted to match the needs and following an analysis the impact on design practice is formulated. Results show the need to combine a wider design exploration capability, in combination with comparative modelling strategies.

Keywords: additive manufacturing, design methodology, design analysis, engineering design

1. Introduction
Products designed for space applications such as launchers and satellite systems represent a challenging category of products from an engineering design perspective. Unlike other industries (Pawlicki, 2015), these products are produced in small batches and have to cope with the extreme conditions and requirements of launching and, at the same time, satellite applications have to be able to have a useful life of more than 15 years after successful orbit insertion. (Castet and Saleh, 2009). The recent advancements made in additive manufacturing (AM) technologies, are attractive for space applications. AM allows for weight and material volume minimization, which are indeed ideal drivers in costly products to be produced in low production volumes (Mellor et al., 2014). At the same time, AM increases the opportunity to apply novel strategies in the design activity. For instance, topology optimization combined with additive manufacturing (Brackett et al., 2011) offers the opportunity to manufacture products with minimal weight, by solving material distribution problems.
From a design perspective, however, AM represent a radically new way of manufacturing and brings a great deal of uncertainty. Engineering design strategies offer tactics for engineers to systematically guide the development of products (Cross, 2000). Such methods address the generation and application of technical knowledge to control and improve the product along its lifecycle. For example, design for manufacturing and assembly (DfMA) methods (Boothroyd et al., 2010) target the support of design products in such a way that they are easy to manufacture and assemble. However, regarding AM, the guidelines and strategies suggested by conventional ‘design for X’ (DfX) methods (Boothroyd et al., 2010) do not constitute a fully relevant design support. New guidelines and strategies on how to “design for additive manufacturing” (DfAM) are needed. Literature (e.g., Thompson et al., 2016) has provided a number of insights into DfAM but have often been derived from lessons learned from a number of industrial contexts - such as biomedical or automotive (Guo and Leu, 2013) - which do not present the same critical conditions such as the ones encountered by space applications.

This paper investigates the impact on design when introducing additive manufacturing in space applications. Through a literature and an empirical study, the restraints and challenges of space applications are matched together with the existing design strategies for additive manufacturing. The results of these studies are then discussed, pointing at the centrality of "modelling" as a crucial design strategy in the context of DfAM. This research was organized around the following research questions:

- *RQ1: How can DfAM methods be a support to effectively introduce additive manufacturing in space applications?*
- *RQ2: How can DfAM methods be extended to match the constraints imposed by the introduction of additive manufacturing in space applications?*

2. Research methodology

The study can be described as a Research Clarification (RC) in the Design Research Methodology (DRM) framework (Blessing and Chakrabarti, 2009). The research results come from the combination of a systematic literature mapping study (Kitchenham and Charters, 2007) and an empirical study in a Swedish-funded research project. The literature mapping was conducted by cross-analysing and 'matching' two neighbouring research areas – namely, research on design for additive manufacturing methods (DfAM domain), and research on the introduction of additive manufacturing in space products. The empirical study was realized in two workshops that joint the efforts of Swedish universities and aerospace industries with the objective of demonstrating the feasibility of introducing and qualifying additive manufacturing technologies in space applications.

2.1. Systematic literature mapping

A literature review on a topic identifies and evaluate existing areas or gaps demanding research (Wohlin, 2014; Alabama University, 2018). From the most popular methodologies for performing a literature review, systematic literature review and systematic literature mapping study, in this article a systematic literature mapping study was preferred. This methodology was preferred because it focuses on broad research questions reviewing substantial number of publications and aims for publication classification to achieve a high understanding of the research area (Barn et al., 2017).
The literature mapping was performed on two sets of academic publications found in SCOPUS database, as it is the largest citation and abstract database of peer reviewed literature (Elsevier, 2018). The first SCOPUS search focused on research on DfAM methods and the second, instead, focused on research on AM applications in the space industry. As presented in Figure 1, the scope was limited to the subject area of engineering and to journal articles, conference papers and book chapters. Regarding the search conducted on the DfAM domain, the procedure was limited to title, abstracts and keywords and the results obtained were filtered by title, abstract and then by full-text content. Previous research (Bertoni et al., 2017) shows the importance of explicitly defining inclusion and exclusion criteria for filtering publications during literature reviews. The inclusion criteria, in this case, were to preserve entries related with the design methodologies applied to physical products (hence are related to the actual hardware, or mechanical, design) and that are intended to be fabricated using AM techniques.
Regarding the search conducted on the industrial application (space) domain, the search was limited to keywords, being then filtered by title, abstract and full text. The inclusion criteria were preserving entries related with the space industry and its implementation of AM, with a focus on the design of physical products with engineering content (hence related to the actual hardware design of a space product) and the used methodologies and encountered challenges during this process. For both searches, redundant items were removed and the remaining list was complemented with other entries implementing a procedure of backward snowballing (Wohlin, 2014) with the purpose of reaching publications outside the range of SCOPUS and increase the validity of the literature mapping. Finally, due to the rapid development of AM technologies, the final list was enhanced with not-peer reviewed new publications from the industrial/technology domain. The resultant list of articles is composed of 58 items.

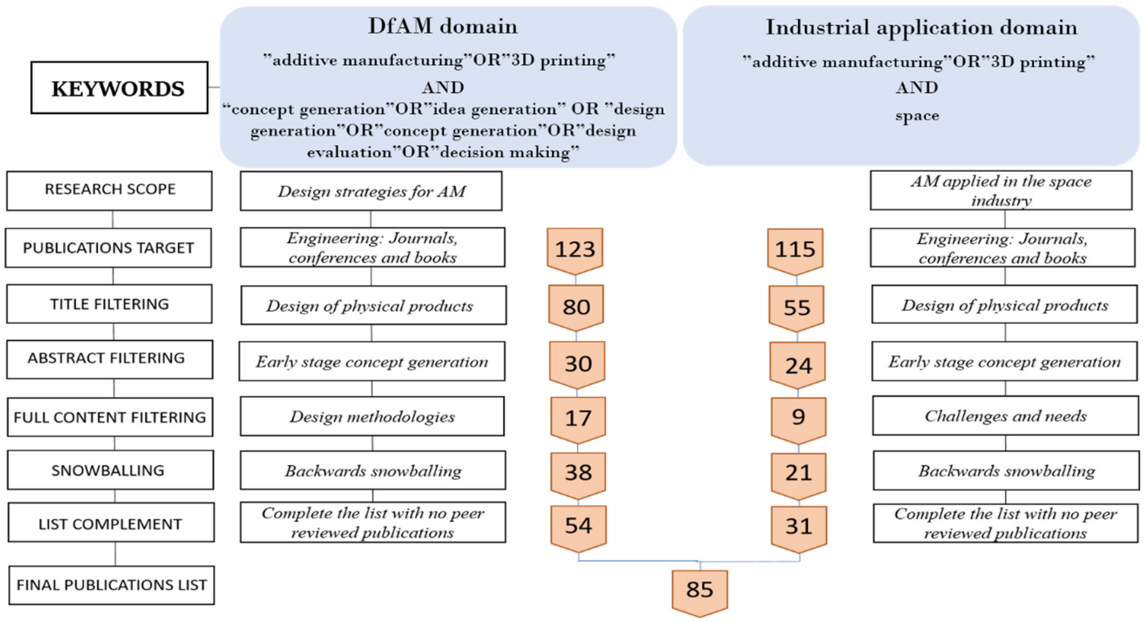


Figure 1. Systematic literature mapping procedure

2.2. Empirical study

Participants in the two workshops were industrial experts from three space equipment manufacturers, who are active in roles that relate to the generation and selection of new design concepts. The main aspects of interest during the workshop were related to two main dimensions:

- How AM enables the generation of new radical design concepts
- How AM engineering design phases have to be conducted, with a special emphasis on the qualification and certification stage

Problems in the current situations as well as wishes for the future were discussed. The workshop benefited from the collective analysis and idea generation on three case components presented by each of the company partners. The empirical data has been collected by observations using field notes and reflections, which were then distributed to the participants of the workshop discussion. Follow-up phone meetings were conducted with the participations for verification and exchange statements.

3. Research findings

This section presents the different results obtained from the two literature mapping studies performed, as well the findings from the empirical study conducted.

3.1. Literature mapping

On the first part of this chapter, the results from the mapping in the DfAM domain are presented. This part exhibits benefits, and constraints mentioned in the DfAM literature and tools and objectives found among DfAM methodologies. In the second part of this chapter, the results from AM applications in the space domain are presented and needs and challenges for AM in the context of space products are collected and explained. To wrap up, a cross analysis chart of both literature analyses is presented.

3.1.1. DfAM domain: Benefits and constraints from designing with additive manufacturing

From the DfAM domain search, a number of benefits and constraints emerged. The most recurrent benefit of AM is an unprecedented design freedom, 26 related articles were found, such as (Wits et al., 2013; Rosen, 2014; Laverne et al., 2015; Rias et al., 2017). This freedom enabled by 3D printing technologies includes shape, function, material and hierarchical complexity making possible product

customization (Rosen, 2013; Salonitis, 2016; EOS, 2018) without the need of tooling or increased manufacturing time and cost (Yang et al., 2016; Kannan, 2017). AM allows also the possibility of structural design (18 articles) (Thompson et al., 2016) enabling constructions with anisotropic materials, material gradient (Dimitrov et al., 2006; Gordon et al., 2016; Goehrke, 2017; Stratasys, 2018) and multiscale structures. Weight reduction is also an advantage, using strategies like topology optimization (Yang et al., 2016), or part consolidation (22 articles) in the form of integrated, internal or embedded designs and interlocking features (Gibson et al., 2010; Gutierrez et al., 2011; Calì et al., 2012; Davis et al., 2016; Advantech, 2017) facilitating assembly (Hague et al., 2003; Mahto and Sniderman, 2017).
Constraints found related to AM include a constrained material availability (9 articles) (Thompson et al., 2016; Shao, 2017), performance and standardization of machines and processes (10 articles) (Laverne et al., 2015; Tilton et al., 2017; Stratasys, 2018) and CAD software adapted and developed for AM (13 articles) (Rosen, 2007; Salonitis, 2016; HSSMI, 2017; Käfer and Seit, 2017; Renishaw, 2018). Post processing is also a concern (19 articles) regarding the removal of support material, manufacturing tolerance limitations, releasing of thermal tension or improvement of surface finishing (Thomas, 2009; Klahn et al., 2015; Custompart, 2018; Hassanin et al., 2018). Another concern is feature size limitations (15 articles) like maximal angle between the part surface and the machine plate, that if surpassed creates the need of using support structure. Also, resolution of features, like graven fonts or maximum size of enclosed hollow volumes that, if exceeded will create the need of using internal support structure impossible to remove afterwards (Gordon et al., 2016; Kumke et al., 2016; Blösch-Paidosh and Shea, 2017; Kannan, 2017; Seepersad et al., 2017; MSCSoftware, 2018). Moreover, defects and their detection (10 articles) are problematic, as they can reduce fatigue life or facilitate crack propagation. There is a lack of knowledge of the physical phenomena that take place during the AM process and a difficulty to predict the quality of a piece (Ponche, 2013; MSCSoftware, 2018). Parts manufactured with AM have a complex thermal history that involves repeated fusion, directional heat extraction, and rapid solidification (Frazier, 2014; Loughborough, 2018).

3.1.2. DfAM strategies

22 entries were found related to methodologies for DfAM, the objectives of those methodologies are: design guidelines for fostering innovation/ideation (41%), for achieving part optimization (efficiently allocation of material) (30%) and for achieving part consolidation through reduction of the amount of parts to assemble (29%). Moreover, on the analyzed entries, the main strategies used for achieving those objectives are function modelling (54%), geometrical modelling (43%) and mathematical/physical modelling (3%).
The guidelines to foster innovation are design methodologies focused mostly on taking advantage of AM´s design freedom. For this purpose, is frequently used *function modelling* to decompose the product function in hierarchical sub functions implementing tools like the modular three-dimensional function graph presented by Boyard (2015). Other strategies combine function modelling with idea generation tools, like the use of databases or analogies (Emmelmann et al., 2011; Brandt et al., 2013; Rias et al., 2016). *Geometrical modelling* is also implemented through topology optimization (Maheshwaraa et al., 2011; Vayre et al., 2012; Panesar et al., 2014) and *mathematical/physical modelling*, especially for modelling material behavior through mathematical equations (Chen et al., 2016). Methodologies focusing on part optimization aim to achieve an optimized version of a design, allocating better the material to minimize the material amount used, reducing weight, building time and manufacturing cost (Yang et al., 2016; Hu et al., 2017). For this purpose, *function* (Boyard et al., 2013) and *geometrical modelling* (Ponche et al., 2012; Ponche, 2013; Ponche et al., 2014) are implemented. Part consolidation have the objective of reducing the amount of assembly parts of a design through function integration, this approach can reduce the overall assembly time and cost (Calì et al., 2012; Maidin et al., 2012; Yang et al., 2015; Essa et al., 2017) using function integration through *function modelling* (Yang et al., 2015).
From the literature mapping of the DfAM domain, can be concluded that the main efforts are directed to the exploration of benefits and constraints of AM and their translation into methodologies for aiding the designer to achieve mostly innovative designs, part consolidation and part optimization. The focus seems to be directed to take advantage of AM design freedom, with little regard about the introduction of this technology into the industrial application sector.

3.1.3. Industrial application domain: Current focus of research on AM applications in space

Needs and challenges regarding the application of AM in the context of space products are presented in the left part of Figure 2. The main focus is set on the need of developing comparative modelling strategies to aid the process of qualification (Wang et al., 2008) and help ensuring quality (32%). Qualification is needed for the establishment of a sufficient technology readiness level (Mankins, 1995), diminishing the level of uncertainty related with a new technology and is a need is present in all the extension of the production chain (Yeong et al., 2013; Gockel et al., 2014; Kim et al., 2014; Martukanitz et al., 2014; Uriondo et al., 2015; Farinia, 2018). Second, comes (17%) the need to develop methodologies for design (Goehrke, 2017), like the ones mentioned on the previous section, and thirdly, 14% corresponds to the need of clear set of rules for printing process set-ups. Printing set-ups refers to considerations to be made for starting the printing process, from choosing machine and materials to selecting printing direction. These set-ups affect properties like: thermal, electric conductivity, tensile and yield strength, surface roughness, part accuracy and the use of support (Zhang and Bernard, 2013; Clinton, 2016; Blösch-Paidosh and Shea, 2017).

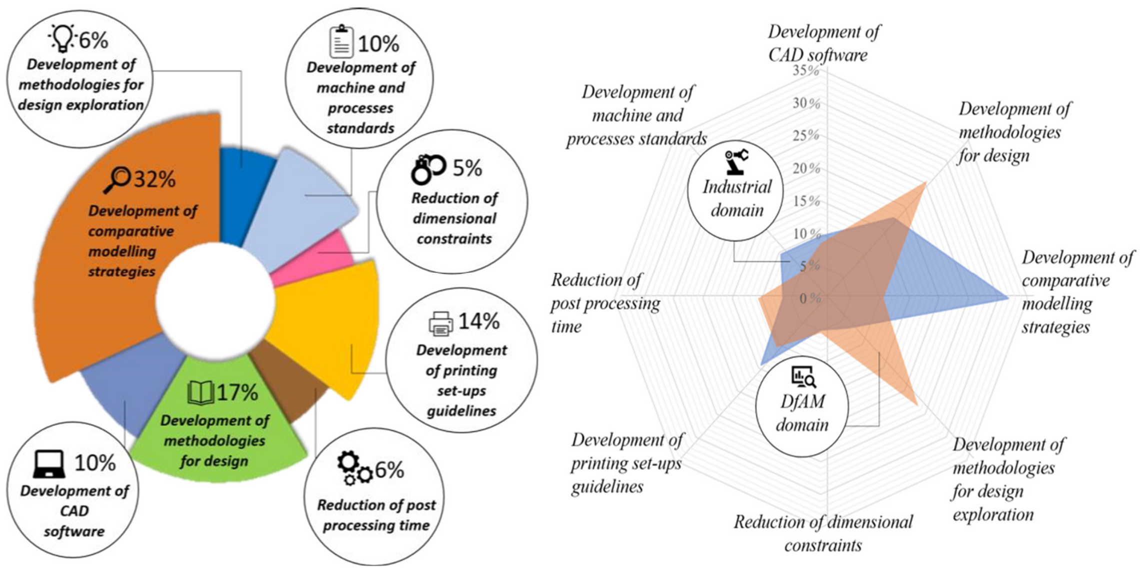


Figure 2. Left, needs and challenges to apply AM in space products; Right, comparison of needs and challenges from the industrial domain with challenges addressed in the DfAM domain

Machine processes and standards (10%) are also in need, as they help improving quality and qualification, as well as increasing market opportunities (Munguía et al., 2008; Johnston et al., 2014; TNO, 2014; Swerea, 2017; Kramer, 2018). Standards currently applied in traditional manufacturing are not suitable for AM technologies (Monzón et al., 2015). The need to develop or adapt CAD software to AM is also mentioned (10%) as traditional CAD tools for conventional manufacturing are obsolete. Furthermore, current CAD systems developed or adapted for AM are still in development (McClintock, 2017) and there are few CAD packages for helping the engineers to fully adopt AM (Dordlofva et al., 2016; McEleney, 2017; Hendley, 2018) and those packages have still limitations (Ghidini, 2013; Gibson et al., 2015; Yang and Zhao, 2015; McClintock, 2018). The need of methodologies for aiding design exploration and generating innovative ideas is also mentioned (6%), as well as the need to improve the technology to, for, example, diminish dimensional constraints (5%) and, the need to reduce post treatment (6%) recognized as a contributor for increasing lead time and cost (Schmelzle et al., 2015; Dordlofva et al., 2016; Grunewald, 2016; ESA, 2017; Hu et al., 2017; McClain, 2017; Schelmetic, 2017). A poor surface finish, for example, must be treated with complementary processes due to the negative effect it has on fatigue resistance, heat transfer or contact among internal surfaces (Kumbhar and Mulay, 2016; Lindwall et al., 2017; Martin-Iglesias et al., 2017).

For concluding this section, the right side of Figure 2 present the needs from the industrial application domain compared with the needs addressed in the DfAM domain. The areas of interest of the industrial and DfAM domain are misaligned, as the industrial domain seems primordially interested on developing comparative modelling strategies and the DfAM domain, in developing methodologies for design exploration and methodologies for design.

3.2. Empirical study

The first phase was focused on design exploration, were the industrial partners presented products currently manufactured with traditional processes, with the intention to be redesign for AM. In that context, companies and academic partners shared their expertise with a brainstorming session and collaborated to create a variety of redesign concepts for the targeted products. It was observed in this phase a tendency to generate concepts similar to the preexisting ones and a difficulty to integrate the benefits and constraints of AM. The major manufacturing and qualification concerns expressed by the industrial partners are related with the nature and detection of defects, as well as their impact on performance, material behavior and capabilities, surface finishing and geometric accuracy. On the second phase, function modeling was implemented, the case-products were decomposed into hierarchical functions to help the design process and assist the process of qualification, qualifying features and geometry regarding their associated function and manufacturing restrictions.
Whilst the top-level functions from the original and the redesign models are expected to be the same, the constraints emerging from classical, often subtractive, manufacturing technologies can be relieved. Using this approach, the original functions and manufacturing constraints were identified, and the constraints emerging from traditional manufacturing were relieved. However, when conceptualizing the use of AM, benefits in geometrical freedom are realized, but there are also new constraints added. Introducing function modelling and constraints replacement in the workshops, enabled the discovery and removal of obsolete functions, the better realization of the existing ones and the possibility to include new. Figure 3 shows an example about the redesign of an annulus profile. In the example, an annulus shape manufactured with traditional methodologies is redesign for AM. In Figure 3 (left) the annulus is printed without redesign and the diameter is larger than a maximum diameter threshold for avoiding the need for support structures (AM constrain). Hence, the annulus requires the use of support structures. Considering this constrain since the early design allows for a new design that reduces the use of support (Figure 3, right).

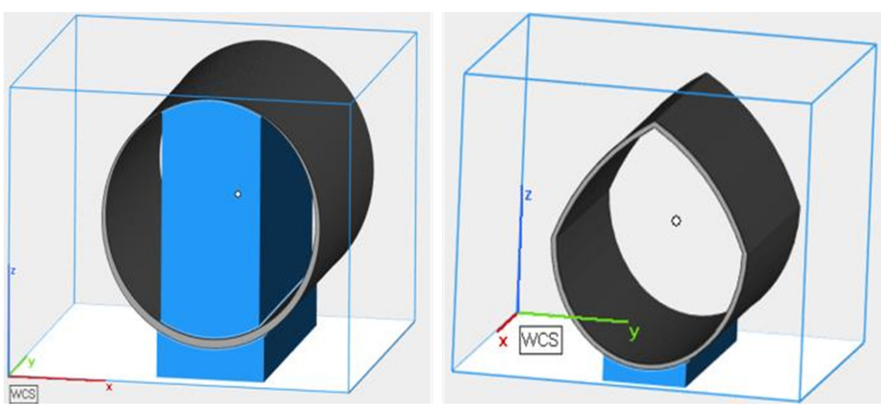


Figure 3. Annulus profile example elaborated using Materialise® Magics constraints replacement when designing with AM leading to geometry transformation to avoid undesired support structures

4. Discussion: The need for a novel modelling strategy to introduce AM in space applications

The results from the literature and the empirical study suggest that for AM to be introduced in space applications, the parts should go through a process of redesign, to take full advantage of this technology

(Salonitis, 2016). However, the designing task in additive manufacturing is difficult as it involves a process of unlearning the design guidelines for traditional manufacture. For facilitating the design process, many DfAM methodologies are currently being developed and most of them (42% of the entries in the literature study) are focused on aiding the exploration of innovative design and more than half (54%) of the entries in the literature study focus on the adoption of *function modelling* to decompose the product function in hierarchical sub functions (Boyard, 2015), where new designs that fulfil the same (or new) functions can be generated through idea generation tools, like the use of databases or analogy methods - such as biomimicry (Emmelmann et al., 2011; Brandt et al., 2013; Rias et al., 2016).

Through the use of such DfAM methods radical new designs and geometries can be generated (for example, the annulus profile in Figure 3), but this introduces an element of novelty that challenges decision-making processes during the design activity. The industrial practitioners taking part in the empirical study elaborate on the fact that - when making decisions - novel design alternatives are always compared to a base reference design, where a solid experience and confidence exists. Novel designs need to be proven to be "better" in comparison with existing solutions. These decisions have to be made early (already on a concept level), where design changes can be made spending little time and effort. The downside of making decisions early is that the full set of information may not be available at these stages Practitioners hence stress the need in the early design phases to generate information and knowledge about the "goodness" of such new designs for AM, in comparison to existing solutions. This need is mapped also in the results of the literature study, where research on AM introduction in space application stress the interest for *comparative modelling strategies* (32% of the entries) and sets little attention on design exploration (6%) (Figure 2, right).

This discussion suggests the importance of *modelling* in order to exploit both design exploration opportunity and confidence in decision making. From the results of the literature analysis two main trends for modelling strategies emerge. Function modelling allows to represent current as well as novel designs simultaneously. Yet, to allow full comparison in the context of AM for space applications, manufacturing constraints should also be represented in a function model. In this way, constraints can be removed and introduced, allowing the generation of new insights in the design process already from the early phases. These types of representation could also become input to other comparative modelling strategies, such as the identification of critical 'features' to be tested in a physical artefact (intended to act as a 'qualificator') where critical design properties – regarding for example quality, surface finishing, or fatigue life – can be compared to existing solutions already since early design.

5. Conclusions

This paper studied how the introduction of additive manufacturing (AM) in space applications impacts the design phases, combining a literature and an empirical study in collaboration with three manufacturers.

- The literature review indicates that - at present - focus is dominated by 1) the need to understand current constraints and behaviour of AM, and 2) ways to benefit from the increased degrees of freedom using AM.
- Few studies are found on a systematic and generic modelling approach for DfAM. This need is instead stressed by industrial practitioners in the empirical study. Such a modelling approach can support the generation of insights and learnings that match the characteristics of AM with the design objectives/functions driving the novel designs.

Preliminary findings indicate that a modelling approach able to represent functionality and constraints linked to different product concepts is crucial for real world design cases. For further work, it is suggested to explore the modelling of functions and constraints when re-designing for AM.

Acknowledgments

The authors gratefully acknowledge the financial support from the Swedish National Space Technology Research Program (NRFP) and the Swedish aerospace companies participating on the workshops for the RIQAM project that made possible the data collection needed for the empirical study.

References

Advantech (2017), *Additive Electronics Manufacturing Technology*. [online] Advantech. Available at: http://www.advantechus.com/additive-electronics-manufacturing.html (accessed 27.02.2018).

Alabama University (2018), *How to Conduct a Literature Review: Types of Literature Reviews*. [online] University of Alabama Libraries. Available at: http://guides.lib.ua.edu/c.php?g=39963&p=253698 (accessed 27.02.2018).

Barn, B., Barat, S. and Clark, T. (2017), "Conducting Systematic Literature Reviews and Systematic Mapping Studies", *Proceeding ISEC '17 /the 10th Innovations in Software Engineering Conference*, *Jaipur, India,* ACM New York, NY, USA, pp. 212-213. https://doi.org/10.1145/3021460.3021489

Bertoni, M., Rondini, A. and Pezzotta, G. (2017), "A systematic review of value metrics for PSS design*", Procedia CIRP*, Vol. 64, pp. 289-294. https://doi.org/10.1016/j.procir.2017.03.057

Blessing, L. and Chakrabarti, A. (2009), *DRM: A Design Research Methodology*, Springer, London. https://doi.org/10.1007/978-1-84882-587-1

Blösch-Paidosh, A. and Shea, K. (2017), "Design heuristics for additive manufacturing", *Proceedings of ICED'17 / the 21st International Conference on Engineering Design, Vol. 5*, *Vancouver, Canada, August 21-25, 2017*, The Design Society, Glasgow, pp. 91-100.

Boothroyd, G., Dewhurst, P. and Knight, W. (2010), *Product design for manufacture and assembly*, CRC Press.

Boyard, N., Rivette, M., Christmann, O. and Richir, S. (2013), "A design methodology for parts using additive manufacturing", *Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal*, Taylor & Francis, London, pp. 399-404. https://doi.org/10.1201/b15961-74

Brackett, D., Ashcroft, I. and Hague, R. (2011), "Topology optimization for additive manufacturing", *Proceedings of SFF 2011 / the 22nd Annual International Solid Freeform Fabrication Symposium, Vol. 1, Austin, Texas, August 8-10, 2011,* The University of Texas at Austin, pp. 348-362.

Brandt, M., Sun, S., Leary, A. and Liu, Q. (2013), "High-value SLM aerospace components: from design to manufacture", In: Subic, A. (Ed.), *Advanced Materials Research,* Vol. 633, pp. 135-147. https://doi.org/10.4028/www.scientific.net/AMR.633.135

Calì, J., Calian, D., Amati, C., Kleinberger, R., Steed, A. et al. (2012), "3D-printing of non-assembly, articulated models", *ACM Transactions on Graphics (TOG),* Vol. 31 No. 6. https://doi.org/10.1145/2366145.2366149

Castet, J.-F. and Saleh, J.H. (2009), "Satellite and satellite subsystems reliability: statistical data analysis and modelling", *Reliability Engineering and System Safety*, Vol. 94 No. 11, pp. 1718-1728. https://doi.org/10.1016/j.ress.2009.05.004

Chen, T., Mueller, J. and Shea, K. (2016), "Design and fabrication of a bistable actuator with multi-material additive manufacturing", *Proceedings of SFF 2016 / the 27th Annual International Solid Freeform Fabrication Symposium- An additive manufacturing conference, Austin, Texas, August 8-10, 2016*, The University of Texas at Austin, pp. 2060-2076.

Clinton, R. (2016), *NASA's In Space Manufacturing Initiative and Additive Manufacturing Development and Quality Standards Approach for Rocket Engine Space Flight Hardware*. [online] NASA, Marshall Space Flight Center. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160004218.pdf (accessed 28.02.2018).

Cross, N. (2000), *Engineering design methods*, John Wiley and Sons Ltd, Chichester, West Sussex.

Custompart (2018), *Milling*. [online] Custompartnet. Available at: http://www.custompartnet.com/wu/milling (accessed 27.02.2018).

Davis, M., Middendorf, J., Garg, N. and Ohanian, O.J. (2016), "Additively manufactured components with embedded instrumentation", *Proceedings of ASME 2016 International Mechanical Engineering Congress and Exposition, Vol. 2, Phoenix, Arizona, November 11-17, 2016,* ASME, pp. V002T02A066. https://doi.org/10.1115/IMECE2016-66697

Dimitrov, D., Schreve, K. and de Beer, N. (2006), "Advances in three-dimensional printing – state of the art and future perspectives", *Rapid Prototyping Journal,* Vol. 12 No. 3, pp. 136-147. https://doi.org/10.1108/13552540610670717

Dordlofva, C., Lindwall, A. and Törlind, P. (2016), "Opportunities and Challenges for Additive Manufacturing in Space Applications", *Proceedings of NordDesign 2016, Vol. 1, Trondheim, Norway, August 10-12, 2016*, The Design Society, Glasgow, pp. 401-410.

Elsevier (2018), *About Scopus*. [online] Elsevier. Available at: https://www.elsevier.com/solutions/scopus (accessed 27.02.2018).

Emmelmann, C., Sanders, P., Kranz, J. and Wycisk, E. (2011), "Laser Additive Manufacturing and Bionics: Redefining Lightweight Design", *Physics Procedia, Vol. 12*, pp. 364-368. https://doi.org/10.1016/j.phpro.2011.03.046

EOS (2018), *Complex geometries*. [online] EOS. Available at: https://www.eos.info/additive_manufacturing/for_your_business/complex_geometries (accessed 27.02.2018).

ESA (2017), *New centre introducing ESA projects and space firms to 3D printing*. [online] ESA. Available at: http://www.esa.int/Our_Activities/Space_Engineering_Technology/New_centre_introducing_ESA_projects_and_space_firms_to_3D_printing (accessed 02.03.2018).

Essa, K., Hassanin, H., Attallah, M.M., Adkins, N.J., Musker, A.J. et al. (2017), "Development and testing of an additively manufactured monolithic catalyst bed for HTP thruster applications", *Applied Catalysis A: General*, Vol. 542, pp. 125-135. https://doi.org/10.1016/j.apcata.2017.05.019

Farinia (2018), *How Can Additive Manufacturing Help the Aerospace Sector?* [online] Farinia Group. Available at: http://www.farinia.com/additive-manufacturing/industrial-3d/can-additive-manufacturing-save-the-aerospace-sector (accessed 27.02.2018).

Frazier, W.E.J. (2014), "Metal Additive Manufacturing: A Review", *Journal of Materials Engineering and Performance*, Vol. 23 No. 6, pp. 1917-1928. https://doi.org/10.1007/s11665-014-0958-z

Ghidini, T. (2013), *European Space Agency Perspective on Additive Manufacturing (AM)* [online] ESA. Available at: http://www.3d-printing-additive-manufacturing.com/media/downloads/47-d1-09-00-b-tommaso-ghinini-esa.pdf (accessed 28.02.2018).

Gibson, I., Goenka, G., Narasimhan, R. and Bhat, N. (2010), "Design rules for additive manufacturing", *Proceedings of SFF 2010 / the 21st Annual International Solid Freeform Fabrication Symposium, Austin, Texas, August 9-11, 2010*, The University of Texas at Austin, pp. 705-716.

Gibson, I., Rosen, D.W. and Stucker, B. (2015), Additive Manufacturing Technologies: Rapid prototyping to Direct Digital Manufacturing, Springer, New York. https://doi.org/10.1007/978-1-4939-2113-3

Gockel, J., Beuth, J. and Taminger, K. (2014), "Integrated control of solidification microstructure and melt pool dimensions in electron beam wire feed additive manufacturing of Ti-6Al-4V", *Additive Manufacturing*, Vol. 1-4, pp. 119-126. https://doi.org/10.1016/j.addma.2014.09.004

Goehrke, S. (2017), *Aerosint Brings Multi-Material Capabilities to Powder Bed 3D Printing*. [online] 3D Print.com. Available at: https://3dprint.com/190661/aerosint-multi-material-3dp/ (accessed 27.02.2018).

Goehrke, S. (2017), *The ESA Explores 3D Printing on Earth and Beyond*. [online] 3D Print.com. Available at: https://3dprint.com/187581/esa-3d-printing/ (accessed 02.03.2018).

Gordon, E., Shokrani, A., Flynn, J., Goguelin, S. Barclay, J. and Dhokia, V. (2016), "A surface modification decision tree to influence design in additive manufacturing", In: Setchi, R., Howlett, R., Liu, Y. and Theobald P. (Eds.), *Sustainable Design and manufacturing,* Springer, Cham, pp. 423-434. https://doi.org/10.1007/978-3-319-32098-4_36

Grunewald, S. (2016), *ESA Taps BEEVERYCREATIVE to Help Develop a 3D Printing Breadboard for the ISS*. [online] 3DPrint.com. Available at: https://3dprint.com/115418/beeverycreative-esa-iss/ (accessed 02.03.2018).

Guo, N. and Leu, M.C. (2013), "Additive manufacturing: technology, applications and research needs", *Frontiers of Mechanical Engineering*, Vol. 8 No. 3, pp. 215-243. https://doi.org/10.1007/s11465-013-0248-8

Gutierrez, C., Salas, R., Hernandez, G., Muse, D., Olivas, R. et al. (2011), "CubeSat fabrication through additive manufacturing and micro-dispensing*", Proceedings of IMAPS 2011 / the 44th International Symposium on Microelectronics, Long Beach, California, October 9-13, 2011*, International Microelectronics Assembly and Packaging Society, pp. 1021-1027. https://doi.org/10.4071/isom-2011-THA4-Paper3

Hague, R., Campbell, R. and Dickens, P. (2003), "Implications on design of rapid manufacturing", *Journal of Mechanical Engineering Science*, Vol. 17 No. 1, pp. 25-30. https://doi.org/10.1243/095440603762554587

Hassanin, H., Elshaer, A., Benhadj-Djilali, R., Modica, F. and Fassi, I. (2018), "Surface Finish Improvement of Additive Manufactured Metal Parts ", In: Gupta, K. (Ed.), *Micro and Precision Manufacturing*, Springer, Cham, pp. 145-164. https://doi.org/10.1007/978-3-319-68801-5_7

Hendley, N. (2018), *CAD still key for additive design work*. [online] Canadian metal working. Available at: https://www.canadianmetalworking.com/article/automationsoftware/cad-still-key-for-additive-design-work (accessed 10.03.2018).

HSSMI (2017), *Overcoming Limitations of Additive Manufacturing Through Advances in CAD Technology*. [online] HSSMI A manufacturing innovation institute. Available at: http://hssmi.org/news/overcoming-limitations-additive-manufacturing-advances-cad-technology/ (accessed 27.02.2018).

Hu, R., Chen, W., Li, Q. and Liu, S. (2017), "Design Optimization Method for Additive Manufacturing of the Primary Mirror of a Large-Aperture Space Telescope", *Journal of Aerospace Engineering*, Vol. 30 No. 3. https://doi.org/10.1061/(ASCE)AS.1943-5525.0000690

Johnston, M., Werkheiser, M., Snyder, M. and Edmunson, J. (2014), "3D Printing in Zero-G ISS Technology Demonstration", *Proceedings of AIAA SPACE 2014 Conference and Exposition, San Diego, CA, August 4-7, 2014*, AIAA SPACE Forum. https://doi.org/10.2514/6.2014-4470

Käfer, S. and Seit, J. (2017), *3D Printing-Possibilities and Current Limitations*. [online] SpotLightMetal. Available at:https://www.spotlightmetal.com/3d-printing-possibilities-and-current-limitations-a-669410 (accessed 27.02.2018).

Kannan, T. (2017), *Design for additive manufacturing*. [online] ASSEMBLY. Available at: https://www.assemblymag.com/articles/93741-design-for-additive-manufacturing (accessed 27.02.2018).

Kim, T., Yue, S., Zhang, Z., Jones, E., Jones, J. and Lee, P. (2014), "Additive manufactured porous titanium structures:Through-process quantification of pore and strut networks", *Journal of Materials Processing Technology*, Vol. 214 No. 11, pp. 2706-2715. https://doi.org/10.1016/j.jmatprotec.2014.05.006

Kitchenham, B. and Charters, S. (2007), Guidelines for performing systematic literature reviews in software engineering, Keele University, Durham, UK.

Klahn, C., Leutenecker, B. and Meboldt, M. (2015), "Design Strategies for the Process of Additive Manufacturing", *Procedia CIRP,* Vol. 36, pp. 230-235. https://doi.org/10.1016/j.procir.2015.01.082

Kramer, H. (2018), *ISS Utilization: 3D Print (3D Printing in Zero-G Technology Demonstration)*. [online] EO Portal. Available at: https://directory.eoportal.org/web/eoportal/satellite-missions/i/iss-3d-print (accessed 02.03.2018).

Kumbhar, N. and Mulay, A. (2016), "Post Processing Methods used to Improve Surface Finish of Products which are Manufactured by Additive Manufacturing Technologies: A Review*", Journal of The Institution of Engineers (India),* Series C, pp. 1-7. https://doi.org/10.1007/s40032-016-0340-z

Kumke, M., Watschke, H. and Vietor, T. (2016), "A new methodological framework for design for additive manufacturing", *Journal of virtual and physical prototyping*, Vol. 11 No. 1, pp. 3-19. https://doi.org/10.1080/17452759.2016.1139377

Laverne, F., Segonds, F., Anwer, N. and Le Coq, M. (2015), "Assembly based methods to support innovation in design for additive manufacturing: An exploratory case study", *Journal of Mechanical Design*, Vol. 137 No. 12, pp. 121701. https://doi.org/10.1115/1.4031589

Lindwall, A., Dordlofva, C. and Öhrwall Rönnbäck, A. (2017), "Additive manufacturing and the product development process: insights from the space industry", *Proceedings of ICED'17 / the 21st International conference of engineering design, Vol. 5, Vancouver, Canada, August 21-25, 2017*, The Design Society, Glagow, pp. 345-354.

Loughborough University (2018), *About Additive Manufacturing*. [online] Loughborough University. Available at: http://www.lboro.ac.uk/research/amrg/about/materials/ (accessed 27.02.2018).

Maheshwaraa, U., Seepersad, C. and Bourel, D. (2011), "Topology design and freeform fabrication of deployable structures with lattice skins", *Rapid Prototyping Journal*, Vol. 17 No. 1, pp. 5-16. https://doi.org/10.1108/13552541111098581

Mahto, M. and Sniderman, B. (2017), *3D opportunity for electronics*. [online] Deloitte insights. Available at: https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-printed-electronics.html (accessed 27.02.2018).

Maidin, S., Campbell, I. and Pei, E. (2012), "Development of a design feature database to support design for additive manufacturing", *Assembly Automation*, Vol. 32 No. 3, pp. 235-244. https://doi.org/10.1108/01445151211244375

Mankins, J. (1995), Technology readiness levels, Advanced Concepts Office, Office of Space Access and Technology NASA.

Martin-Iglesias, P., Van Der Vorst, M., Gumpinger, J. and Ghidini, T. (2017), "ESA's recent developments in the field of 3D-printed RF/microwave hardware", *Proceedings of the 11th European Conference on Antennas and Propagation, Paris, France, May 19-24, 2017*, IEEE, pp. 553-557.

Martukanitz, R., Michaleris, P., Palmer, T., DebRoy, T., Liu, Z.-K. et al. (2014), "Toward an integrated computational system for describing the additive manufacturing process for metallic materials", *Additive Manufacturing*, Vol. 1-4, pp. 52-63. https://doi.org/10.1016/j.addma.2014.09.002

McClain, M. (2017), *Development and Characterization of a Novel Additive Manufacturing Technology Capable of Printing Propellants with High Solids Loadings*. [online] NASA. Available at: https://www.nasa.gov/directorates/spacetech/strg/nstrf_2017/Novel_Additive_Manufacturing_Technology (accessed 28.02.2018).

McClintock, C. (2017), *How additive manufacturing is changing 3D CAD*. [online] PTC Available at: https://www.ptc.com/en/cad-software-blog/how-additive-manufacturing-is-changing-3d-cad (accessed 10.03.2018).

McClintock, C. (2018), *5 signs your CAD tools fail at 3D printing*. [online] PTC Available at: https://www.ptc.com/en/cad-software-blog/5-signs-your-cad-tools-fail-at-3d-printing (accessed 10.03.2018).

McEleney, J. (2017), *The future of 3D printing: 5 additive manufacturing trends to look for in 2017*. [online] On shape. Available at: https://www.onshape.com/cad-blog/the-future-of-3d-printing-5-additive-manufacturing-trends-to-look-for-in-2017 (accessed 10.03.2018).

Mellor, S., Hao, L. and Zhang, D. (2014), "Additive manufacturing: A framework for implementation", *International Journal of Production Economics*, Vol. 149, pp. 194-201. https://doi.org/10.1016/j.ijpe.2013.07.008

Monzón, M., Ortega, Z., Martínez, A. and Ortega, F. (2015), "Standardization in additive manufacturing: activities carried out by international organizations and projects", *International Journal of Additive Manufacturing Technology*, Vol. 76 No. 5-8, pp. 1111-1121. https://doi.org/10.1007/s00170-014-6334-1

MSCSoftware (2018), *Additive Manufacturing*. [online] MSC Software. Available at: http://www.mscsoftware.com/application/additive-manufacturing (accessed 27.02.2018).

Munguía, J., de Ciurana, J. and Riba, C. (2008), "Pursuing successful rapid manufacturing: a users' best-practices approach", *Rapid Prototyping Journal*, Vol. 14 No. 3, pp. 173–179. https://doi.org/10.1108/13552540810878049

Panesar, A., Brackett, D., Ashcroft, I., Wildman, R. and Hague, R. (2014), "Design optimization strategy for multifunctional 3D printing", *Proceedings of SFF 2014 / the 25th Annual International Solid Freeform Fabrication Symposium, Austin, Texas, August 4-6, 2014*, The University of Texas at Austin, pp. 1179-1193.

Pawlicki, J. (2015), *Comparing Innovation Aviation and Aerospace to Other Industries - Part two: Aero vs. electro*. [online] DOM. Available at http://www.dommagazine.com/article/comparing-innovation-aviation-and-aerospace-other-industries-part-two-aero-vs-electro (accessed 12.03.2018).

Ponche, R. (2013), Méthodologie de conception pour la fabrication additive, application `a la projection de poudres, PhD thesis, Ecole Centrale de Nantes (ECN).

Ponche, R., Hascoët, J., Kerbrat, O. and Mognol, P. (2012), "A new global approach to design for additive manufacturing", *Virtual and Physical Prototyping*, Vol. 7 No. 2, pp. 93-105. https://doi.org/10.1080/17452759.2012.679499

Ponche, R., Kerbrat, O., Mognol, P. and Hascoët, J. (2014), "A novel methodology of design for additive manufacturing applied to additive laser manufacturing process", *Robotics and Computer-Integrated Manufacturing*, Vol. 30 No. 4, pp. 389-398. https://doi.org/10.1016/j.rcim.2013.12.001

Renishaw (2018), *Renishaw fact sheet: additive manufacturing*. [online] Renishaw. Available at: http://resources.renishaw.com/en/details/renishawfact-sheet-additive-manufacturing--58726 (accessed 27.02.2018).

Rias, A., Bouchard, C., Segonds, F. and Abed, S. (2016), "Design for additive manufacturing: A creative approach", *Proceedings of the DESIGN 2016 / 14th International Design Conference, Dubrovnik, Croatia, May 16-19, 2016*, The Design Society, Glasgow, pp. 411-420.

Rias, A., Segonds, F., Bouchard, C. and Abeds, S. (2017), "Towards additive manufacturing of intermediate objects (AMIO) for concepts generation", *International Journal on Interactive Design and Manufacturing*, Vol. 11 No. 2, pp. 301-315. https://doi.org/10.1007/s12008-017-0369-0

Rosen, D. (2007), "Design for additive manufacturing: A method to explore unexplored regions of the design space", *Proceedings of SFF 2007 / the 17th Annual International Solid Freeform Fabrication Symposium, Austin, Texas, August 6-8, 2007,* The University of Texas at Austin, pp. 402-415.

Rosen, D. (2013), "Computer-Aided Design for Additive Manufacturing of Cellular Structures", *Journal of computer-aided design and applications*, Vol. 4 No. 5, pp. 585-594. https://doi.org/10.1080/16864360.2007.10738493

Rosen, D. (2014), "Design for Additive Manufacturing: Past, Present, and Future Directions", *Journal of Mechanical Design*, Vol. 136 No. 9, pp. 090301. https://doi.org/10.1115/1.4028073

Salonitis, K. (2016), "Design for additive manufacturing based on the axiomatic design", *International Journal of Additive Manufacturing Technology*, Vol. 87 No. 1-4, pp. 989-996. https://doi.org/10.1007/s00170-016-8540-5

Schelmetic, T. (2017), *NASA Projects Advance Technology for Additive Manufacturing in Space*. [online] Design News. Available at: https://www.designnews.com/materials-assembly/nasa-projects-advance-technology-additive-manufacturing-space/111729844756546 (accessed 02.03.2018).

Schmelzle, J., Kline, E., Dickman, C., Reutzel, E., Jones, G. and Simpson, T. (2015), "(Re)Designing for Part Consolidation: Understanding the Challenges of Metal Additive Manufacturing", *Journal of Mechanical Design*, Vol. 137 No. 11, pp. 111404. https://doi.org/10.1115/1.4031156

Seepersad, C., Jared, A. and Sharpe, C. (2017), "The need for effective design guides in additive manufacturing", *Proceedings of ICED'17 / 21st International Conference on Engineering Design, Vol. 5, Vancouver, Canada, August 21-25, 2017*, The Design Society, pp. 21-25.

Shao, S. (2017), *The limitation of the Additive Manufacturing (3D Printing)*. [online] MSING051 and MSINGC02. Available at: https://medium.com/msing051/the-limitation-of-the-additive-manufacturing-3d-printing-7b6ff7df521f (accessed 27.02.2018).

Stratasys (2018), *ASTM Additive Manufacturing Standards: What You Need to Know*. [online] Stratasys direct manufacturing. Available at: https://www.stratasysdirect.com/company/quality-assurance/astm-additive-manufacturing-standards-what-you-need-to-know (accessed 27.02.2018).

Stratasys (2018), *Multi-Material 3D Printing*. [online] Stratasys direct manufacturing. Available at: http://www.stratasys.com/solutions/additive-manufacturing/multi-material-3d-printing (accessed 27.02.2018).
Swerea (2017), *State-of-the-art for Additive Manufacturing of Metals – Report from Ramp-Up*. [online] Swerea-Swedish research. Available at: https://www.swerea.se/en/news/state-of-the-art-for-additive-manufacturing-of-metals-report-from-ramp-up (accessed 27.02.2018).
Thomas, D. (2009), The Development of Design Rules for Selective Laser Melting, PhD thesis, University of Wales.
Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R.I. et al. (2016), "Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints", *CIRP Annals-Manufacturing Technology*, Vol. 65 No. 2, pp. 737-760. https://doi.org/10.1016/j.cirp.2016.05.004
Tilton, B., Dobner, E. and Holdowsky J. (2017), *3D opportunity for standards*. [online] Deloitte Insights. Available at: https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-standards-for-3d-printed-products.html (accessed 27.02.2018).
TNO (2014), *Support Action for Standardisation in Additive Manufacturing - Project summary document*. [online] SASAM. Available at: http://cordis.europa.eu/docs/results/319167/final1-project-summary-sasam-final.pdf
Uriondo, A., Esperon-Miguez, M. and Perinpanayagam, S. (2015), "The Present and Future of Additive Manufacturing in the Aerospace Sector: A Review of Important Aspects", *Journal of Aerospace Engineering*, Vol. 229 No. 11, pp. 2132-2147. https://doi.org/10.1177/0954410014568797
Vayre, B., Vignat, F. and Villeneuve, F. (2012), "Designing for Additive Manufacturing", *Procedia CIRP*, Vol. 3, pp. 632-637. https://doi.org/10.1016/j.procir.2012.07.108
Wang, W., Azarian, M.H. and Pecht, M. (2008), "Qualification for product development", *Proceedings of the ICEPT-HDP 2008 International Conference on Electronic Packaging Technology & High-Density Packaging, Shangai, China*, IEEE, pp. 1-12. https://doi.org/10.1109/ICEPT.2008.4606933
Wits, W., Weitkamp, S. and van Es, J. (2013), "Metal additive manufacturing of a high-pressure micro-pump", *Procedia CIRP,* Vol. 7, pp. 252-257. https://doi.org/10.1016/j.procir.2013.05.043
Wohlin, C. (2014), "Guidelines for snowballing in systematic literature studies and a replication in software engineering", *Proceeding EASE '14 / the 18th International Conference on Evaluation and Assessment in Software Engineering*, *London, UK*, ACM, New York, USA. https://doi.org/10.1145/2601248.2601268
Yang, S. and Zhao, Y.F. (2015), "Additive manufacturing-enabled design theory and methodology: a critical review", *International Journal of Advanced Manufacturing Technology*, Vol. 80 No. 1-4, pp. 327-342. https://doi.org/10.1007/s00170-015-6994-5
Yang, S., Tang, J. and Zhao, Y. (2015), "A new part consolidation method to embrace the design freedom of additive manufacturing", *Journal of Manufacturing Processes*, Vol. 20 No. 3, pp. 444-449. https://doi.org/10.1016/j.jmapro.2015.06.024
Yang, S., Tang, J. and Zhao, Y.F. (2016), "Assembly-level design for additive manufacturing: issues and benchmark", *Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 2A, Charlotte, North Carolina*. ASME, pp. V02AT03A028. https://doi.org/10.1115/DETC2016-59565
Yeong, W.Y. and Chua, C.K. (2013), "A quality management framework for implementing additive manufacturing of medical devices", *Virtual and Physical Prototyping*, Vol. 8 No. 3, pp. 193-199. https://doi.org/10.1080/17452759.2013.838053
Zhang, Y. and Bernard, A. (2013), "Using AM feature and Multi-attribute decision making to orientate part in Additive Manufacturing", *International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal,* Taylor & Francis, London, pp. 411-416. https://doi.org/10.1201/b15961-76

Olivia Borgue, PhD student
Chalmers University of Technology, Industrial and Material Science
Slätten 3B, 41661 Göteborg, Sweden
Email: borgue@chalmers.se

Article B

DRIVERS AND GUIDELINES IN DESIGN FOR QUALIFICATION USING ADDITIVE MANUFACTURING IN SPACE APPLICATIONS

Dordlofva, Christo (1); Borgue, Olivia (2); Panarotto, Massimo (2); Isaksson, Ola (2)

1: Luleå University of Technology; 2: Chalmers University of Technology

ABSTRACT

In recent years, reducing cost and lead time in product development and qualification has become decisive to stay competitive in the space industry. Introducing Additive Manufacturing (AM) could potentially be beneficial from this perspective, but high demands on product reliability and lack of knowledge about AM processes make implementation challenging. Traditional approaches to qualification are too expensive if AM is to be used for critical applications in the near future. One alternative approach is to consider qualification as a design factor in the early phases of product development, potentially reducing cost and lead time for development and qualification as products are designed to be qualified. The presented study has identified factors that drive qualification activities in the space industry and these “qualification drivers” serve as a baseline for a set of proposed strategies for developing “Design for Qualification” guidelines for AM components. The explicit aim of these guidelines is to develop products that can be qualified, as well as appropriate qualification logics. The presented results provide a knowledge-base for the future development of such guidelines.

Keywords: New product development, Additive Manufacturing, Design for X (DfX), Design for Qualification, Space Applications

Contact:
Dordlofva, Christo
Luleå University of Technology
Business Administration, Technology and Social Sciences
Sweden
christo.dordlofva@ltu.se

Cite this article: Dordlofva, C., Borgue, O., Panarotto, M., Isaksson, O. (2019) ‘Drivers and Guidelines in Design for Qualification Using Additive Manufacturing in Space Applications’, in *Proceedings of the 22nd International Conference on Engineering Design (ICED19),* Delft, The Netherlands, 5-8 August 2019. DOI:10.1017/dsi.2019.77

1 INTRODUCTION

The space industry is seeing an increase in demand for access to space to enable space-based services and human space flight, with new actors opting for market shares. This implies a need for a business-oriented evolution of technology and product development, decreasing cost and time to market. Space products traditionally involve a costly product development process for manufacturing low volumes (from one-off production to tens of parts per year) of high-performance products to be used in harsh environments. However, the space industry is currently in the middle of a transition due to the advent of the so called NewSpace companies such as SpaceX or Virgin Galactic (Salt, 2013). SpaceX, for instance, is planning to launch a constellation of more than 4000 low costs satellites to provide internet connection via space, and expect to have an operating network covering the US by 2020 (BBC News, 2018). This is one example of how cost and lead time reduction are becoming true drivers for space companies (Öhrwall Rönnbäck and Isaksson, 2018). In this context, additive manufacturing (AM) is a technology that has the potential to reduce lead-times and manufacturing costs (O'Brien, 2018). The use and development of AM is growing rapidly within the aerospace industry, but not without challenges since the whole product development process is impacted by the introduction of AM. One challenge of implementing AM in space applications is to demonstrate that products and processes meet specified quality and reliability requirements (Dordlofva and Törlind, 2017). The process dedicated to assuring that quality and reliability requirements are met is called qualification (Gerling *et al*., 2002). Previous studies (Dordlofva and Törlind, 2017) suggest that qualification aspects should be addressed already in the early phases of product development to ascertain that a product designed for AM can be qualified. However, the knowledge about the AM process chain is still low compared to traditional manufacturing processes (O'Brien, 2018). For this reason, it is difficult to predict the process outcome and consequently what to plan for in the qualification activities. The objective of this article is to provide a knowledge base for the creation of qualification guidelines to be utilised when designing products for a new manufacturing technology such as AM. Future research will utilise this knowledge to develop such guidelines, which would have the purpose of supporting the design of a product that can be qualified (Design for Qualification) and support the design of the qualification activities (the qualification logic). To guide this work, one research question was defined: *How can qualification be considered in the early phases of product development of AM parts for space applications?*

In the theoretical framework of this paper, product qualification is first presented in general terms to provide a context in which the challenge of design and qualification of AM products is discussed. The method used for data collection and analysis is then presented, where the interview study at two companies in the European space industry is described. The results and analysis of the interviews are thereafter presented following the same structure as in the theoretical framework by first providing the findings regarding product development and qualification in general, concluding on motivators for qualification activities in the space industry (qualification drivers). Thereafter the use of AM in space applications and the implications of the identified qualification drivers on designing and qualifying AM components are discussed. In this paper, AM is referring to metal Powder Bed Fusion (PBF) technologies, i.e. Electron Beam Melting (EBM) and Laser Beam Melting (LBM).

2 PRODUCT QUALIFICATION

Qualification can be defined as the activities performed to demonstrate that a product or a process meets or exceeds specified quality and reliability requirements (Gerling *et al*., 2002). In manufacturing process qualification, all the procedures that validate that a process meets specified performance and quality requirements are included. Process qualification assures that a process is controlled and produces repeatable qualified products (Tantra and van Heeren, 2013). Product qualification assesses the performance, quality and reliability of products under operational conditions and examines if the product meets the design requirements (Musgrave *et al*., 2009). Developing and qualifying a product and the processes for its manufacturing requires to comprehend how performance and reliability are related to product functionality and application (Gerling *et al*., 2002). Wang *et al*. (2008), state that three different types of qualification activities are performed during a product development process. First, *virtual product qualification* is implemented as means to evaluate the functionality and reliability of a product design without physical tests. Later, during *physical product qualification*, quality and reliability are evaluated based on tests on a qualification hardware. After virtual and physical product qualification, production begins and during the manufacturing, the product's quality is inspected and tested again. The authors consider this process as the third and final phase of the qualification activities, commonly referred to as *quality assurance testing*. The authors also propose that product design activities and qualification activities can include several feedback iterations. If the product design is found not to meet the qualification requirements, it is modified and qualified again before continuing with the next product development phase. For space components, qualification activities are performed on flight-like units at levels and in environments above the design requirements to ensure robustness and design margins (Musgrave *et al.*, 2009). Flight-like units and qualification activities are however generally expensive for space systems (Öhrwall Rönnbäck and Isaksson, 2018) and for that reason, the iteration between product design activities and qualification activities proposed by Wang *et al*., is not necessarily applicable (Dordlofva and Törlind, 2017). These high costs of the qualification activities in the space industry are contradictory with the growing need of reducing cost. However, some authors such as Gerling *et al*. (2002) or Yadav *et al*. (2006) suggest that costs and lead time can be reduced if qualification activities are included earlier in the design process. Pecht (1993), Preussger *et al*. (2003) and Yadav *et al*. (2006) have proposed methodologies and guidelines for the electronics industry focusing on reliability assessment, test activities and test planning early in the development process. However, guidelines for approaching product design considering how the product should be qualified are missing. In product design, there are various design practices or supports that aim to maximise different aspects of a product. These are included in the Design for X (or Design for Excellence) methodology, where X represents product aspects such as functionality, manufacturability, safety, quality, or serviceability (Bralla, 1996). Designing a product to assure that it can be qualified should also be considered for products where qualification is an important part of the development (Pecht, 1993). Despite this, explicit *Design for Qualification* supports are lacking. DfX techniques provide three types of support: *qualitative guidelines*, *metrics*, and *feasibility checks* (Holt and Barnes, 2010). Metrics provide ways to measure a design's performance linked to the X aspects of the product that are sought for (e.g. cost or reliability), while feasibility checks aim at evaluating the X aspects linked to different life phases of the product (e.g. manufacture and assembly or end-o-life). Qualitative guidelines on the other hand are more generic, open for interpretation, and flexible, supporting the designers to e.g. understand what features and properties that should be included or avoided (ibid.). In this paper, Design for Qualification guidelines refer to this latter category.

2.1 Design and qualification in additive manufacturing

The use of AM in aerospace applications is increasing and major OEM:s continuously push the limit of the technologies. General Electric has for example developed and tested the Advanced Turboprop engine with 12 parts manufactured by AM (GE, 2017). However, information about the criticality level of parts that have been introduced in different applications is scarce (Gorelik, 2017), and within the space industry, secondary structures and other non-critical parts have been in focus (Brandão *et al*., 2017). This is due to that the qualification of AM processes and parts manufactured using AM remains a challenge (Frazier, 2014), and there is a lack of understanding of AM processes and standardised approaches to ascertain the quality of AM parts (Seifi *et al*., 2017). The need for AM standards has been acknowledged by the AM community and there are for example already nine published ISO standards and 25 under development (ISO/TC-261, 2019). However, the need for standardised procedures in industry is urgent, and for example NASA has expressed that they "cannot wait for national standard development organizations to issue AM standards", and have developed their own for space flight hardware (Clinton, 2018, p. 33). One of the complexities with AM that make standardisation challenging is that parts exhibit material characteristics such as anisotropic and location dependent properties, defects, and rough surfaces (Seifi *et al*., 2017). It has also been shown that part geometry can impact these material characteristics (ibid.), putting additional responsibility on design engineers to understand the capabilities of AM processes. Design for AM (DfAM) has received much attention with the increased interest for AM in industry and academia. The need to support engineers early in product development to allow them to explore the design potentials enabled by AM is often highlighted, and such DfAM methods have been proposed by e.g. Kumke *et al*. (2018) and Laverne *et al*. (2017). However, there is less focus on methods to explicitly support engineers in designing products that can be qualified. Holistic and relevant DfAM frameworks have been proposed by e.g. Kumke *et al*. (2016) and Zhu *et al*. (2017), where the importance of consideration for the whole manufacturing process capabilities (including pre and post AM) are stressed. Explicit measures for dealing with the issue of process and product qualification early in the product development process are however lacking. O'Brien (2018) argues that at the current stage of AM maturity, sound DfAM for space applications should for example include considerations for part complexity, inspection and testing due to the intrinsic characteristics of AM parts.

3 METHODOLOGY

The data collection for this paper are semi-structured interviews carried out at two large companies that design and manufacture space components (Company A and Company B). Semi-structured interviews were preferred since the topic in study is complex and the concept of qualification can be interpreted in various ways, requiring lengthy explanations and follow up questions (Bryman and Bell, 2015). The companies were selected for the study since they both have a long history in the space industry delivering sub-system components to established international customers. The companies specialise in different components as presented in Table 1, which can reveal distinctive aspects of the qualification activities.

Table 1. Participating companies in the study.

Company	Description	Employees
A	The company is developing complex and high-performance components for aerospace. The studied part focuses on product development and manufacturing of sub-system components for civil aircraft engines and launcher applications.	17 000
B	The company is operating within different segments of the aerospace industry. The studied part is providing products for in-orbit applications and the responsibility includes the whole chain from R&D to sales for several product areas.	1 400

A total of 12 engineers were interviewed (eight at Company A, four at company B) with a range from 12 to 30 years of experience in the aerospace industry. The sampling of interviewees was done to have a mixture of different company roles; design engineers, method and material specialists, chief engineers, and department and division managers. It should be noted that Company A design and manufacture components for both civil aircraft and launcher applications, and that some of the interviewed engineers currently work with aircraft applications. All of the interviewees had experience from several phases of product development, and both companies are working towards the implementation of AM. Some of the interviewees had little experience of AM, and some had worked with AM for several years. All interviews were performed in Swedish and all quotes in this paper are consequently translated by the authors. The interviews were conducted by two of the authors, one of which have several years of experience in design of space systems and is situated as an industrial Ph.D. student at a company within the space industry. The other interviewing author is new to the space industry and was therefore able to take the role as an external auditor (Creswell, 2014).

The interviews lasted 40-60 minutes, and an interview guide was used with questions divided into two focus areas; *Qualification in product development* and *Use of AM in space applications*. In addition, questions about the interviewees background were included. After five initial interviews, the interview guide was revisited with a few questions reformulated to narrow down the focus on the most relevant aspects for the research question (Bryman and Bell, 2015). All but one of the interviews were recorded and transcribed (one of the interviewees wished not to be recorded, instead both authors took notes during the interview and then summarised it together). To clarify the empirical data and identify recurring and dominant themes, selective coding was used. Data reduction in the form of pattern matching and data displays was utilised to synthesise the findings (Miles and Huberman, 1994). The pattern matching involved the selection of eight categories based on topics identified before performing the interviews, with each category belonging to one of the two focus areas, and one category labelled 'Other'. The authors that performed the interviews individually read through each transcript and highlighted quotes related to these categories. The result from the coding was compiled in a spreadsheet that allowed comparison between the interviews. The quotes in the spread sheet were then condensed into a text document where similar quotes were grouped together. This text was then jointly read by the two interviewing authors. During this process, two of the eight initial categories were slightly reformulated to better fit the interviewees answers, and to include aspects from 'Other'. One new category was created within the focus area *Use of AM in space applications*.

4 RESULTS

The outcome from the analysis are presented as follows. First, findings from the focus area *Qualification in product development* are presented, followed by a synthesis on how these findings can be used to account for qualification in the early phases of product development. Second, the findings from the focus area *Use of AM in space applications* are given, followed by a discussion on what the implications of these are on designing AM parts while considering qualification activities.

4.1 How is qualification considered in product development?

When asked if and how qualification is considered in the product development process, most of the interviewees answered that qualification plays an early role in product development since otherwise development and production would become very expensive as the amount of testing would increase significantly. Qualification plans are initiated early and are then developed along with the product. The assumptions that are made during product development with regard to manufacturing process outcome (e.g. material properties), what level of process control is possible in production, the available knowledge about the product or the manufacturing process (e.g. internal company legacy and external third-party standards), and the criticality of the product function were mentioned as aspects that impact a qualification logic. However, it was also noted that qualification is often not considered early enough. As one interviewee at Company A expressed it; *"Today, qualification comes in when you start to converge towards a concept. Optimally, it should already come in when you have a set of product solutions"*. Similarly, one interviewee from Company B expressed that *"it is seldom that we allow the work with qualification to impact the design work [...] rather, it is the design/product development that impacts what we need to qualify"*. Interviewees at Company B also mentioned that they try to re-use previous designs as much as possible since the amount of qualification that is needed for proven designs usually decrease. For this reason, it is also possible that the company increase the requirements on qualification for a certain product to make it more versatile and adaptable for future products. It was also stressed by one of the more senior engineers at Company A that there is not one way to do qualification; *"for a new process [...] there is very little of ready recipes for how to qualify, without having a clear picture of what knowledge that has to be built. It is all very intimately connected. Often the word qualification is misused as a recipe that can be used"*. Another comment from a few interviewees at Company A was that system requirements are important considerations in product development. Understanding what customers and regulating bodies are expecting is essential. This also has the effect that qualification is something of "grey zone" in that the dialogue with the customer is important, where approaches to qualification can be suggested, and different customers can have different views of what is acceptable for showing compliance to specifications and regulations.
These results suggest that qualification is product and process dependent, since the assumptions made during product development and the requirements from the system the product will function in, influence the qualification logic. However, the qualification logic does not usually impact the design activities. Moreover, the qualification activities are not always tailored for one product but can include margins for similar products that might be developed in the future. A difference could be seen here between the companies since Company A usually have purposely designed products for a specific system with less possibility to reuse the same product in a new system. Qualification activities also depend on the customer's and third-party standards and regulations that must be followed. In this context, qualification is a challenging phase as there is no explicit "recipe" for how to qualify.

4.1.1 Strategical and financial aspects of qualification

Both companies rely on program funding together with their customers to be able to develop new products and technologies, hence relationships with customers are important for future business. This has been discussed in previous research as one characteristic of product development in the space industry (Lindwall *et al*., 2017). Since qualification is part of the product development, the cost of qualification is also financed by the customer. It became clear during the interviews that the market shift in the space industry has an impact on how product development is carried out at the two companies. As indicated by previous research (Öhrwall Rönnbäck and Isaksson, 2018), flexibility in design, cost-reduction, reduced time to market, and an increase in produced units (in production) were all aspects that were mentioned. As one interviewee said: *"It´s market competitiveness of course, it's all about being cheap and fast"*. From a qualification perspective some implications of this change were given:

- More responsibility for the design and qualification is pushed on to the design organisation, i.e. sub-system component suppliers such as Company A and B (mentioned by Company A and B).
- To reduce cost, the pressure has increased to use less number of manufactured components that go through the process of qualification, and consequently also to consider what needs to be qualified through testing (Company A).
- The demand for an increase in produced units in production means that cheaper components must be used to be competitive. However, these are less reliable and more difficult to qualify according to traditional qualification requirements (Company B).

The interviews indicate that cost and time-to-market reduction are primordial to assure market competitiveness, where company profit is a factor to consider. The pressure for increasing production volumes may need to decrease the requirements on product reliability if cost, time-to-market and profit goals shall be feasible as companies try to reduce their qualification efforts. A well-established knowledge base for the creation of qualification guidelines would support engineers to design adequate qualification activities for either low or large production volumes. Moreover, the early implementation of qualification guidelines in the design process could reduce the cost of qualification activities as products are designed for qualification.

4.2 Qualification drivers for product development in space applications

Synthesising the results presented above, a number of motivators for qualification activities in space industry were deduced. *These motivators are labelled qualification drivers since they drive the requirements set on the product qualification, and the decisions behind the establishment of a qualification logic*. Figure 1 presents a diagram where the identified qualification drivers are shown along with how they are linked to the product development, the product qualification, and the creation of Design for Qualification guidelines.

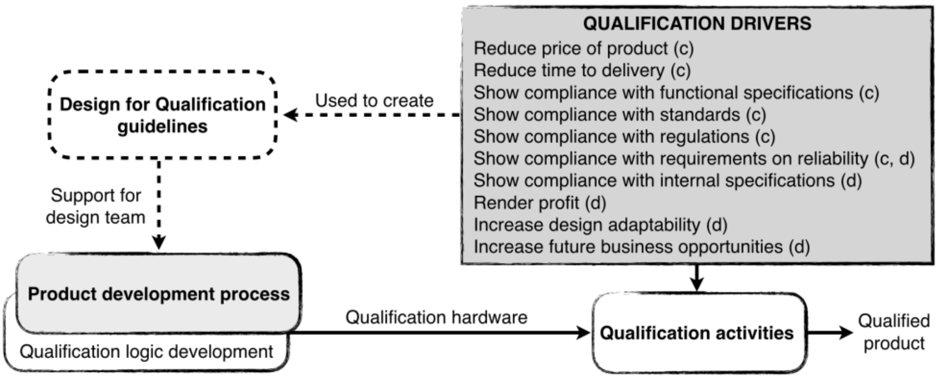


Figure 1. Identified qualification drivers for product development in space applications (c=driver for customer satisfaction, d=driver for design organisation satisfaction).

From the perspective of the companies there are two stakeholders in the development and qualification of a product. The customer that finances and/or purchases the product, and the companies themselves that design and manufacture the product, i.e. the design organisation. The qualification drivers are related with the satisfaction of either customer ('c' in Figure 1), or design organisation ('d' in Figure 1). To achieve customer satisfaction, qualification activities must aim to:

- Reduce overall product price and time to delivery: *"(..) it's all about being cheap and fast"*.
- Show compliance with product functional and technical specifications: the product must perform the functions required by the customer.
- Show compliance with general standards and regulations: Standards are usually third-party and regulations can be either from a governing body (e.g. ECSS from ESA) or specifications from a customer.
- Show compliance with requirements on reliability: Different customers are willing to accept different amounts of risks. It was specifically mentioned that NewSpace companies are willing to accept a higher risk than traditional space companies.

To achieve design organisation satisfaction, qualification activities must aim to:

- Show compliance to requirements on reliability: While some customers were mentioned to accept a higher risk, this was also said to impose an increased responsibility on the design organisation to be liable for failures, implying decisions on risk acceptance.
- Show compliance with internal specifications: Design organisations with internal specifications can impose more stringent requirements than e.g. general standards.
- Render company profit: Product development has to render profitable business cases.
- Increase adaptability of product designs for future business opportunities: design organisations can increase the requirements on qualification for a certain product to make it versatile and adaptable for future products.

The qualification activities and the accomplishment of the above-mentioned objectives for customer and design organisation satisfaction are highly dependent of the capabilities of the design organisation to develop and manufacture products. For that reason, company capabilities (and capabilities of any suppliers used) have to be considered in product design and qualification logic development as well. These capabilities include aspects such as the activities that can be performed as part of the qualification processes (e.g. inspection) or the manufacturing technologies that are available to the company. These capabilities are related with company experience and knowledge (Dordlofva and Törlind, 2017).

4.3 Challenges and expectations on qualification of additive manufacturing

Comparing the stated reasons why the companies are exploring AM, a difference could be seen in that Company A put more emphasis on the importance of cost reduction. Within Company B, the possibility to come up with new and unique design solutions was explicitly said to be more alluring than reducing cost. However, interviewees from both companies mentioned that there is no pressure from customers to introduce AM. Instead, they expressed that convincing customers to use AM products, and to finance such product development, is a challenge. Two other challenges for AM qualification mentioned by almost all of the interviewees were variation in AM process outcome (i.e. material properties) and lack of knowledge about AM processes. With regard to process outcome, there was a belief among the mechanical and material engineers working with AM that nominal mechanical properties related to strength will not be as much of an issue compared to life related mechanical properties (fatigue and damage tolerance) and the variation that can be seen in material characteristics affecting these properties (e.g. surface roughness and defects). From this perspective, one interviewee from Company A expressed a concern for the increased design freedom that comes with AM: *"You can for example make surfaces in a way that you utilise the material to its maximum with increased average stress in the material […] since you optimise your [part] structure. And the two together become a dangerous combination [referring to material defects]"*. The need to challenge conventional interfaces of components to fully utilise the potential with AM, i.e. to think AM on a system-level, was brought up by a few interviewees. To challenge conventional interfaces could however be difficult since it would imply that e.g. a customer and a component supplier might intrude on traditional responsibilities. It could however also expand the product portfolio and give a better understanding of the system requirements.

Insights into the expectations on AM qualification were also given during the interviews. Building process understanding is the key to be able to show a solid background knowledge for convincing customers that the chosen qualification logic is safe and secure. Therefore, in the near term, it is expected that using established knowledge from traditional manufacturing processes will be necessary, using a conservative approach to AM materials based on testing and analytical verification with safety factors. For life sensitive parts, designing for crack propagation will probably be necessary as opposed to crack initiation (fatigue). For example, this could lead to thicker walls to account for the worst case with regard to e.g. defects. It is foreseen that customers will be very cautious and not willing to bend current qualification requirements for metal materials. As with traditional manufacturing processes, AM processes are expected to be frozen on a set of parameters identified during development and testing. When some of the senior engineers at Company A were asked whether it could be acceptable to have a more expensive qualification of AM parts, they believed that this could be the case for early products in order to learn about the processes and start the discussions on qualification. However, in the long term, using AM has to be a competitive business case, hence decreasing the amount of testing used for each product. There will probably not be one qualification logic that can be used for any AM part, but it will be dependent on product and process. However, there could be process specific requirements on e.g. the number of test specimens that have to be printed with the part.

The interviews indicate that while the companies strive to introduce AM to decrease cost and find new competitive design solutions, their customers are conservative and prefer to use 'what is known' while reducing price. Design for Qualification guidelines should assist companies to give attention to critical areas or features of a product to find design solutions that balance the utilisation of layered manufacturing with the available knowledge of AM process capabilities. For example, topology optimisation is often highlighted as one of the main benefits of AM, but as indicated in the interviews, stress optimisation could for example impose an increased risk of failure for life-limited parts due to rough surfaces and defects. Hence, the assumptions that need to be made during design with regard to material properties, design margins, impact of print direction, testing and inspection etc., should be acknowledged in such guidelines. The importance for a company to introduce AM in a specific product should be assessed to set the acceptance of risk and of cost for qualification and production, especially in the near term when building knowledge about AM processes is crucial.

4.4 Strategies to develop AM qualification guidelines for space applications

The qualification drivers presented in Figure 1 gives an overview of the relevant aspects to be considered in qualification of products for space applications. Relating these with challenges and expectations on AM qualification, strategies for creating Design for Qualification guidelines are proposed in Table 2.

Table 2. Strategies for the development of Design for Qualification guidelines for AM parts.

<table>
<tr><th>Qualification drivers related to customer satisfaction</th><th>Qualification drivers related to design organisation satisfaction</th><th>Strategies for Design for Qualification guidelines with regard to the design of qualification logic (L) and product (P)</th></tr>
<tr><td>Reduce price and time-to-delivery</td><td>Render profit</td><td>Define accepted cost of qualification (L)
Reduce the number of hardware to test (L)
Consider reusing previous designs (L, P)
Assess suitability of using AM (P)
(may depend on system-design)</td></tr>
<tr><td>Show compliance with product functional and technical specifications</td><td></td><td rowspan="2">Assess product criticality (L, P):
System-level requirements
Product requirements
AM process maturity and knowledge
Define applicable AM standards (L, P)
Define applicable AM specifications (L, P)
Define applicable regulations (L)
Assess impact of production volume (L)</td></tr>
<tr><td>Show compliance with standards, regulations, and customer specifications</td><td>Show compliance with internal specifications</td></tr>
<tr><td colspan="2">Show compliance to reliability requirements</td><td>Assess accepted level of risk from customer and design organisation (L, P)</td></tr>
<tr><td></td><td>Increase future business opportunities and adaptability</td><td>Evaluate possibilities and need for adaptability to:
Adapt design margins (P)
Adapt qualification requirements (L)</td></tr>
<tr><td></td><td>Comply with manufacturing capabilities:
AM process
Post-processing
Inspection methods
Test methods</td><td>Define approved AM processes (P)
Assess capabilities to design for: (L, P)
AM (best practices)
Post-processing
Inspection
Assess the use of test artefacts (L, P)
Assess proven qualification logics (L)</td></tr>
</table>

These proposed strategies should aid design organisations in the space industry to develop qualification guidelines to approach product development for AM in a manner that can render products that can be qualified. By developing and implementing Design for Qualification guidelines, planning of qualification activities should be given attention during early product design activities. The strategies stress the need to clarify the current level of AM knowledge within the design organisation (and in general standards), include customer dialogue in the design process to agree on acceptable price and risks, assess the specific product application and the implication of using AM (also on a system-level), define what testing and inspections method that can be used, and what implications there are on future business opportunities. This way, the strategies should facilitate the development of a qualification logic that is suitable for the product, the AM process, the company capabilities, and the customer expectations. It is also considered that by using *guidelines* as support for Design for Qualification, there is flexibility in their application depending on the product, where for example "adaptability" might not be relevant for specific products purposely designed for one system.

5 CONCLUSION

AM has been introduced in the space industry to evaluate its potential to find new competitive design solutions and to decrease cost and lead-time in development and manufacturing. However, there is a need to increase the knowledge about AM process capabilities and AM products to show a solid qualification logic to convince customers that the product function can be guaranteed. Qualification is an integral, but expensive, part of product development in the space industry, and to mitigate time-consuming and costly qualifications activities, the qualification logic should be included as a factor early in the design process. This meaning that, since established qualification approaches for AM parts are still missing (Seifi *et al*., 2017), products should be designed to facilitate an affordable qualification. This paper proposes to assess what knowledge and processes that are available within an organisation to help define a qualification logic that is suitable for the organisation's capabilities. For example, local oversizing might be necessary to account for defects since using traditional design approaches based on established defect densities from material testing and manufacturing process control is too expensive (Frazier, 2014). Unless the qualification strategy is defined when design decisions are made, the cost of qualification might become too large. This implies that qualification strategies need to be established in the early phases of product development, preferably already in the conceptual phase.

In this paper, strategies for the creation of guidelines that should support engineers in the development of qualification strategies for AM space components are presented. For supporting the process of designing parts that can be qualified, several motivators that have an impact on the qualification activities for AM in space applications have been identified. These motivators are labelled *qualification drivers* and serve as a knowledge base for creating guidelines to support the development of a qualification logic, and to support *Design for Qualification*. The study is limited to 12 interviews at two companies within the space industry. Due to this sample limitation the identified qualification drivers should be considered in the context of AM space components and other applications should be further studied. Future research will focus on the development of Design for Qualification guidelines that can be applied in product development of AM products. Future work is also to develop modelling support to complement the guidelines for AM products and to support the associated qualification process.

REFERENCES

BBC News. (2018), "SpaceX launches broadband pathfinders", available at: http://www.bbc.co.uk/news/science-environment-43160073 (accessed 2 December 2018).

Bralla, J.G. (1996), *Design for Excellence*, 1st ed., McGraw-Hill/Knovel - online version.

Brandão, A.D., Gerard, R., Gumpinger, J., Beretta, S., Makaya, A., Pambaguian, L. and Ghidini, T. (2017), "Challenges in Additive Manufacturing of Space Parts : Powder Feedstock Cross-Contamination and Its Impact on End Products", *Materials*, Vol. 10 No. 5. https://doi.org/10.3390/ma10050522

Bryman, A. and Bell, E. (2015), *Business Research Methods*, 4th ed., Oxford University Press, Oxford, UK.

Clinton, R.G. (2018), "Overview of Additive Manufacturing Initiatives at NASA Marshall Space Flight Center", *(Presentation)*, available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001514.pdf (accessed 17 March 2019).

Creswell, J.W. (2014), *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 4th ed., Sage Publications, Thousand Oaks, CA.

Dordlofva, C. and Törlind, P. (2017), "Qualification Challenges with Additive Manufacturing in Space Applications", *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*, Austin, TX, USA, August 2017, pp. 2699–2712.

Frazier, W.E. (2014), "Metal Additive Manufacturing: A Review", *Journal of Materials Engineering and Performance*, Vol. 23 No. 6, pp. 1917–1928. https://doi.org/10.1007/s11665-014-0958-z

GE. (2017), "GE Aviation announces 1st run of the Advanced Turboprop engine", available at: https://www.geaviation.com/press-release/business-general-aviation/ge-aviation-announces-first-run-advanced-turboprop-engine (accessed 15 March 2019).

Gerling, W.H., Preussger, A. and Wulfert, F.W. (2002), "Reliability qualification of semiconductor devices based on physics-of-failure and risk and opportunity assessment", *Quality and Reliability Engineering International*, Vol. 18 No. 2, pp. 81–98. https://doi.org/10.1002/qre.468
Gorelik, M. (2017), "Additive manufacturing in the context of structural integrity", *International Journal of Fatigue*, Vol. 94, pp. 168–177. https://doi.org/10.1016/j.ijfatigue.2016.07.005
Holt, R. and Barnes, C. (2010), "Towards an integrated approach to 'Design for X': an agenda for decision-based DFX research", *Research in Engineering Design*, Vol. 21 No. 2, pp. 123–136. https://doi.org/10.1007/s00163-009-0081-6
ISO/TC-261. (2019), "ISO/TC 261 Technical Committee", available at: https://www.iso.org/committee/629086.html (accessed 15 March 2019).
Kumke, M., Watschke, H., Hartogh, P., Bavendiek, A.K. and Vietor, T. (2018), "Methods and tools for identifying and leveraging additive manufacturing design potentials", *International Journal on Interactive Design and Manufacturing*, Springer, Paris, Vol. 12, pp. 481–493. https://doi.org/10.1007/s12008-017-0399-7
Kumke, M., Watschke, H. and Vietor, T. (2016), "A new methodological framework for design for additive manufacturing", *Virtual and Physical Prototyping*, Vol. 11 No. 1, pp. 3–19. https://doi.org/10.1080/17452759.2016.1139377
Laverne, F., Segonds, F., D'Antonio, G. and Le Coq, M. (2017), "Enriching design with X through tailored additive manufacturing knowledge: a methodological proposal", *International Journal on Interactive Design and Manufacturing*, Springer, Paris, Vol. 11, pp. 279–288. https://doi.org/10.1007/s12008-016-0314-7
Lindwall, A., Dordlofva, C. and Öhrwall Rönnbäck, A. (2017), "Additive manufacturing and the product development process: Insights from the space industry", *Proceedings of the International Conference on Engineering Design, ICED17*.
Miles, M.B. and Huberman, A.M. (1994), *Qualitative Data Analysis: An Expanded Sourcebook*, Sage Publications, Beverly Hills, CA.
Musgrave, G.E., Larsen, A.M. and Sgobba, T. (Eds.). (2009), *Safety Design for Space Systems*, Butterworth-Heinemann.
O'Brien, M.J. (2018), "Development and qualification of additively manufactured parts for space", in Helvajian, H., Piqué, A. and Gu, B. (Eds.), *Proceedings of SPIE, Laser 3D Manufacturing V*, SPIE, pp. 1–14. https://doi.org/10.1117/12.2297204
Öhrwall Rönnbäck, A.B. and Isaksson, O. (2018), "Product Development Challenges for Space Sub-System Manufacturers", *Proceedings of the 15th International Design Conference*, pp. 1937–1944. https://doi.org/10.21278/idc.2018.0534
Pecht, M.G. (1993), "Design for Qualification", *Proceedings of Annual Reliability and Maintainability Symposium*, pp. 1–4.
Preussger, A., Kanert, W. and Gerling, W. (2003), "Reliability qualification of a smart power technology for high temperature application based on physics-of-failure and risk & and opportunity assessment", *2003 IEEE International Reliability Physics Symposium Proceedings.*, pp. 378–384. https://doi.org/10.1109/RELPHY.2003.1197777
Salt, D. (2013), "NewSpace - delivering on the dream", *Acta Astronautica*, Elsevier, Vol. 92 No. 2, pp. 178–186. https://doi.org/10.1016/j.actaastro.2012.08.020
Seifi, M., Gorelik, M., Waller, J., Hrabe, N., Shamsaei, N., Daniewicz, S. and Lewandowski, J.J. (2017), "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification", *JOM*, Vol. 69 No. 3, pp. 439–455. https://doi.org/10.1007/s11837-017-2265-2
Tantra, R. and van Heeren, H. (2013), "Product qualification: a barrier to point-of-care microfluidic-based diagnostics?", *Lab on a Chip*, Vol. 13 No. 12, pp. 2199–2201. https://doi.org/10.1039/c3lc50246e
Wang, W., Azarian, M.H. and Pecht, M. (2008), "Qualification for product development", *2008 International Conference on Electronic Packaging Technology & High Density Packaging*, IEEE, pp. 1–12. https://doi.org/10.1109/ICEPT.2008.4606933
Yadav, O.P., Singh, N. and Goel, P.S. (2006), "Reliability demonstration test planning: A three dimensional consideration", *Reliability Engineering & System Safety*, Vol. 91 No. 8, pp. 882–893. https://doi.org/10.1016/j.ress.2005.09.001
Zhu, Z., Pradel, P., Bibb, R. and Moultrie, J. (2017), "A Framework for Designing End Use Products for Direct Manufacturing Using Additive Manufacturing Technologies", *Proceedings of the 21st International Conference on Engineering Design (ICED17)*, Vol. 5, pp. 327–336.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from LTU Graduate School of Space Technology, the area of advance Production at Chalmers, the EU project RIT (Space for Innovation and Growth), and the Swedish National Space Agency through NRFP (Swedish National Space Research Programme).

Article C

aerospace

MDPI

Article

Constraint Replacement-Based Design for Additive Manufacturing of Satellite Components: Ensuring Design Manufacturability through Tailored Test Artefacts

Olivia Borgue *, Jakob Müller, Alexander Leicht, Massimo Panarotto and Ola Isaksson

Department of Industrial and Materials Science, Chalmers University of Technology, Chalmersplatsen 4, 412 96 Göteborg, Sweden; jakob.muller@chalmers.se (J.M.); alexander.leicht@chalmers.se (A.L.); massimo.panarotto@chalmers.se (M.P.); ola.isaksson@chalmers.se (O.I.)

* Correspondence: borgue@chalmers.se; Tel.: +46-31-772-50-22

Received: 9 October 2019; Accepted: 13 November 2019; Published: 16 November 2019

check for updates

Abstract: Additive manufacturing (AM) is becoming increasingly attractive for aerospace companies due to the fact of its increased ability to allow design freedom and reduce weight. Despite these benefits, AM comes with manufacturing constraints that limit design freedom and reduce the possibility of achieving advanced geometries that can be produced in a cost-efficient manner. To exploit the design freedom offered by AM while ensuring product manufacturability, a model-based design for an additive manufacturing (DfAM) method is presented. The method is based on the premise that lessons learned from testing and prototyping activities can be systematically captured and organized to support early design activities. To enable this outcome, the DfAM method extends a representation often used in early design, a function–means model, with the introduction of a new model construct—manufacturing constraints (Cm). The method was applied to the redesign, manufacturing, and testing of a flow connector for satellite applications. The results of this application—as well as the reflections of industrial practitioners—point to the benefits of the DfAM method in establishing a systematic, cost-efficient way of challenging the general AM design guidelines found in the literature and a means to redefine and update manufacturing constraints for specific design problems.

Keywords: function modelling; AM; constraint modelling; test artefact; manufacturing constraints; DfAM; space components

1. Introduction

Manufacturers of aerospace products are increasingly investigating the capabilities of metallic additive manufacturing (AM). Compared to subtractive manufacturing technologies, AM allows for a greater degree of design freedom, which enables the creation of novel and advanced geometries. Such novel designs and geometries allow substantial reductions in weight and lower "buy-to-fly" ratios (which represent the amount of material used to manufacture a component with the associated scrap). Furthermore, AM has the potential to reduce lead time and manufacturing costs significantly [1,2].

Despite these benefits, AM comes with manufacturing constraints that limit design freedom and reduce the possibility of achieving novel AM geometries that can be produced in a cost-efficient manner [3]. Although research is advancing and providing a host of design guidelines and best practices for AM [4], the magnitude of factors influencing product properties (material, machine setups, powder quality, etc.) has not yet been captured in a way that is applicable for each individual AM process and design scenario [3].

To address the ways manufacturing constraints limit achievable design freedoms, aerospace manufacturers have a number of options, each of which present some serious drawbacks:

1. It is possible to develop a novel design (for example with a complex geometry resulting from a topology optimization) and ensure its quality by testing a large variety of specimens. This option ensures a novel design with the requested qualities, but it substantially impacts the cost of testing to qualify for use. This strategy may be acceptable for technology demonstrations and/or cost-insensitive applications.
2. Manufacturers may deliberately avoid testing many specimens (and the associated costs) and develop a conservative design based on general AM guidelines found in the literature [4]. In this way, the manufacturer efficiently develops a product with the expected quality but misses the opportunity to achieve a more radical—and perhaps better—design. For instance, a general AM design guideline is to avoid the generation of support structures; the minimum overhang angle is 45° [5]; however, authors, such as those of Reference [6], have demonstrated that lower overhang angles may be possible without support structures with adjustments in certain process parameters. This is known as a "fail-safe" strategy.
3. They can deliver a novel and radical AM geometry without performing much testing which can only be considered for applications where failures can be acceptable. Such a strategy is rarely acceptable in space applications to date but is generally denoted as a "safe-fail" strategy.

Such dilemmas are particularly relevant for manufacturers of space components interested in applying AM to achieve more lightweight and cost-efficient components for spacecraft [7]. However, these manufacturers also need to fulfill high-quality requirements related to the extreme conditions associated with rocket launches and satellite operations. These requirements govern the need to ensure safe and reliable functionality of the product and its possible impact on the entire system. Any new technology (or material) used to manufacture a product needs to be certified for use. This need puts the focus on the validity of any new solution proposed to deliver products that meet the requirements accordingly, and all new technologies need to be qualified. For AM, knowledge on how to validate, qualify, and, ultimately, certify new products using AM technologies for applications with high requirements (e.g., structural integrity) is not yet mature. Consequently, the amount of physical testing required to certify new products may be too expensive for large-scale commercial use. This is one reason for focusing on test artifacts that can be used to qualify AM processes for typical designs and to understand how such artifacts can be used to acquire knowledge of design for additive manufacturing (DfAM) methods.

To make use of AM design freedom while ensuring product manufacturability, designers need to find a cost-efficient manner to challenge the general AM design guidelines found in the literature and to redefine the manufacturing constraints that apply to the design scenario of interest (e.g., a specific product, machine, and material). Since DfAM methods can facilitate the consideration of manufacturability aspects in the early stages [8–10], this article presents a DfAM method that extends a type of representation traditionally used in early design—functional modeling [11,12]—with manufacturing constraints modeling. In this approach, the AM constraints are modeled concurrently with the generation and testing of tailored test artifacts. In this way, the knowledge gained from testing such tailored test artifacts can be capitalized by including the manufacturing constraints in the function model and using such AM constraints for component redesign.

1.1. The Impact of Additive Manufacturing (AM) on the Design of Metallic Components for Satellites

The recent advancements made in metal AM technologies are attractive for the development or manufacturing of space components, as the technology promises increased design freedom and reduced manufacturing costs enabled by efficient material allocation. For instance, AM allows for weight and material volume minimization which are drivers of costly production in low production volumes [7]. Metal AM processes are of special interest for the space industry, because they can enable cost reductions and performance increases of high-performance and heavy metal components such as manifolds or engine components.

Researchers and industry practitioners agree that the main challenge when implementing metal AM to design new components is the lack of experience and the large number of uncertainties and unknowns associated with the constraints of the manufacturing process [1]. First, there are non-established standards for machines and processes. Second, there is a lack of knowledge about the physical phenomena that take place during the AM process which creates difficulty in predicting the quality of a piece, as parts manufactured with AM have a complex thermal history that involves repeated fusion, directional heat extraction, and rapid solidification [1,4].

To capture and monitor these complex interactions among different systems, requirements, and interfaces, systems engineering tools, such as that of McInnes et al. [13], have been suggested to support developers. Such tools enable the analysis of system architectures, general performance, and cost but do not support the generation of a concrete design nor the process of making manufacturing-related decisions. For these challenges, most approaches, such as those proposed by Boudjemai et al. [14] or Quincieu et al. [15], use individually generated computer-aided design (CAD) models. However, at the concrete design level, there is a limited ability to systematically capture requirements, constraints, and manufacturing method-related impacts on a design, even in cases where multiple designs are generated and tested such as presented by Boschetto et al. [16]. This leaves developers stuck in the classical iterative design cycle [13], resulting in the abovementioned Option 1.

In short, the recent advancements made in metal AM technologies render this technology attractive for space applications. However, new design mindsets are required to address the lack of knowledge concerning AM technologies.

1.2. Design for AM in Space Applications

Two directions for DfAM approaches have been identified in Reference [17]. On the one hand, opportunity-driven methods focus on design freedom and aim to generate innovative geometries with new functionality, disregarding geometry manufacturability [18]. This can be seen in the work of authors such as Orme et al. [19], where the focus of the development process is placed on exploiting the design freedom offered by AM but paying the price of multiple manufacturing and testing cycles to verify the design (as described in Option 1).

On the other hand, manufacturing-driven methods require minimal changes to a pre-existent component geometry to comply with the manufacturing constraints of AM [4], leading to Option 2. An example of this can be seen in the work presented by Quincieu et al. [15], where the only mentioned adaption to AM is the decision to split a part to fit a required build volume (i.e., application of manufacturing constraints).

Option 3 is exemplified in the case study presented by Thornton et al. [20], where the authors purposely made use of design freedom, albeit only in the form of hexagonal cut-outs in one place, otherwise only scaling the dimensions of the product. This limited use of AM design freedom, alongside a non-systematic approach for capturing and applying of AM constraints is an example of the need for an integrated DfAM method.

While the opportunity-driven and manufacturing-driven approaches initially seem to be exclusive, they are often combined. Research suggests that, as knowledge about AM processes and constraints is limited and in constant evolution, modeling manufacturing constraints can support designers in efficiently managing and using that knowledge [21].

However, authors such as O'Brien [1] have suggested that most extant DfAM methodologies cannot currently compensate for the lack of specific process knowledge about the complex physical phenomena that take place during an AM process.

1.3. Expectations toward a Design for Additive Manufacturing (DfAM) Method for Space Applications

Based on the above-described experiences with AM and satellite design, a DfAM method should be able to represent a product's design space. This design space is delimited with constraints, either from the specific use-case of space applications [7]; material properties, as seen in Booth et al. [22]; or machine-specific impacts, as seen in the dimensioning impact in the work presented by Quincieu et al. [15]. Within the design space, designers can take advantage of design freedom to allow for high-performance designs such as the work presented by Orme et al. [19]. Furthermore, since, in most cases, especially those mentioned by Boudjemai [14], the CAD model plays a large role in the analysis and verification of a product's performance, a close coupling to an easily editable CAD model is desirable.

Several commercial space applications have already been manufactured using a wide range of AM processes for a variety of materials, including titanium, nickel superalloys, steel, and ceramic [23]. These processes and materials have different constraints and their use can lead to different outcomes or qualities (e.g., surface roughness or mechanical properties [24]). The relationship between the input parameters and the expected outcome was schematically shown by Sames et al. [25] and is indeed very complex. As shown, the outcome (failed builds, mechanical properties, feature quality, etc.) is specific for each process and process parameters set. Nevertheless, many of the processes share similar constraints but with different values. For example, a powder bed fusion process may be limited by a build volume of (200 mm × 200 mm × 350 mm), while a powder feed process may be constrained by a volume of (900 mm × 1500 mm × 900 mm) [24]. Identifying these common constraints is of great value for developing DfAM methods.

1.4. Design of Test Artifacts for AM of Space Components

The conceptual phases of the application of DfAM methods for the space industry should include iterative efforts to assess how the manufacturing processes and material properties influence product design and product quality [1]. Assessments of the influence of manufacturing processes and material properties on product design and quality have been widely proposed in the literature about AM test artifacts [23]. Test artifacts (or benchmark artifacts) are implemented to assess and compare the capabilities and limitations of different AM processes. Reference [23] presents extensive reviews of AM test artifacts utilized to compare different AM machines relying on the same or different AM technologies. The authors stated that test artifacts in general are composed of a series of generic geometric features to evaluate dimensional accuracy and other parameters such as surface roughness, mechanical properties, or manufacturing time and costs. However, given that these types of test artifacts contain generic geometric features, they are often not representative of all of the geometric features of a specific product [26]. Moreover, they often lead to the utilization of a potentially unnecessarily large number of test artifacts [27]. The works of Rupal, Ahmad, and Qureshi [27] and Rupal, Secanell, and Qureshi [28] present pioneering approaches to designing test artifacts for AM. Through their novel methods, they carefully analyzed product features critical to product quality and functionality (such as parallelism and concentricity of parallel holes) and built test artifacts based on those findings. However, their methodologies are not concerned with the redesign of a product itself. The findings and lessons learned from the manufacturing of the test artifacts were not explicitly used to improve or modify the product design.

The preceding review suggests the need for a DfAM method that includes prototyping activities to manufacture product-tailored test artifacts and then iteratively modifying the product design based on the results obtained using these test artifacts. In this context, lessons learned from prototyping activities could increase knowledge about AM manufacturing constraints. Moreover, such a method would support product compliance with qualification (activities performed to demonstrate that a product or a process meets or exceeds specified quality and reliability requirements [29]).

Designing products with features that can be qualified facilitates the introduction of AM technologies in highly regulated industries such as the space industry.

In this article, to exploit the design freedom offered by AM while ensuring product manufacturability, a model-based DfAM method is presented. Lessons learned from testing and prototyping activities are systematically captured and organized to support early design activities and reduce late (and costly) redesign and testing efforts. The method establishes a systematic, cost-efficient way of challenging the general AM design guidelines found in the literature to adapt them and make them relevant for a specific product development project and the respective AM parameters of interest.

2. Materials and Methods

This article discusses the results of a project, conducted in cooperation with three Swedish suppliers of space components, which had the objective of demonstrating the feasibility of introducing and qualifying AM technologies in space applications.

The research adopted an action research (AR, [30]) approach featuring several workshops attended by industrial practitioners from the participating companies. Action research is a proven methodology for understanding ill-defined problems in complex organizations that describes how changes in action or practice can positively impact on the community or practice. In this research, AR was performed through a total of five workshops and four follow-up meetings attended by 10 experienced industrial practitioners from the participating companies. The industrial participants were engineers (with 12 to 30 years of designing experience) working in product development.

The first workshop focused on idea generation strategies and presented 10 designs for AM strategies, such as part consolidation and topology optimization, using examples. These strategies are summarized in the work presented by Lindwall and Törlind [31]. The presentation of these strategies acted as random stimuli [32] for the generation of novel concepts. Each company presented one case study product to be redesigned for AM laser powder-bed fusion (LPBF) during the workshops.

In the second workshop, function modeling techniques were implemented for continuing the design process. These techniques were preferred because they are a reliable and well-established way of designing complex products or systems in early design phases [33,34]. The workshop focused on functional decomposition using enhanced function–means modeling (EF–M, [35]). Function models were then developed from this decomposition. Later, interviews were conducted at every participating company to validate the function models. A three-phase DfAM method was then developed and validated in the third workshop. In this method, a function model (FM) tree of a traditional component (manufactured with traditional manufacturing technologies) was constructed. The manufacturing constraints of the traditional technology were included. Next, the original manufacturing constraints were removed from the function tree. Lastly, AM constraints were introduced in the function tree, and the component was redesigned for AM. Details concerning this method can be found in work by Borgue et al. [21].

However, insights from workshops 4 and 5, which were concerned with design manufacturing and qualification, suggested the need for further developing the previous DfAM method.

The observations from the workshops were transcribed and analyzed through content analysis [36]. To protect company-sensitive information and to show the method rather than the technical details of the use cases, significant design features were extracted from the three use cases and combined in the case study presented in this article. The case study features a propellant flow connector which was verified in terms of fidelity with the industry specialists. The flow connector was redesigned for AM and then manufactured and analyzed for validation purposes.

3. Results

The data collection activities performed during the workshops and follow-up meetings highlighted several critical areas to be further explored in the context of AM design for space components.

When designing, the participants recognized that DfAM design constraints (Cs) are related to several factors such as material, machine, design geometry, and process parameters. However, as DfAM experience is scarce, the ways in which those factors constrain product design is sometimes unknown. For instance, when the same design was sent to different providers for manufacturing, geometry accuracy and surface finishing differed greatly.

Moreover, the extensive literature about AM processes was found to be not entirely applicable for specific machine and process setups. General AM design guidelines need to be refined and revaluated through test artifacts to find reliable manufacturing constraints applicable to the AM processes implemented. However, the design of test artifacts that can accurately represent relevant product features that are critical for product performance and qualification was found to be problematic.

The participants reflected on the fact that during early design stages, product design must be performed concurrently with studies on and analysis of the AM manufacturing process and the way it interacts with a product geometry. Many current DfAM strategies do not propose strategies for or palliative methods against AM unknowns such as the manufacturing limitations of a certain machine, defect generation, or surface quality. These reflections lead to the express need to develop design strategies that are able to incorporate these studies and analysis in early design practices.

These findings were used as inputs to propose a DfAM method for space components that included in the design process the iterative manufacturing of product-tailored test artifacts and posterior improvement of the product design.

3.1. Proposed DfAM Method

The proposed model-based DfAM method was developed to exploit the freedom offered by AM design freedom while ensuring product manufacturability. The method is based on function models representing a product's design rationale in the form of hierarchically arranged objects of different types based on the EF–M technique [37]: functional requirements (FRs), design solutions (DSs), and Cs. The proposed model extends the normal use of EF–M modeling by actively using a constraints release and replacement technique. Constraints release and replacement represents a novel strategy for identifying critical geometrical features in a design that need to be tested for manufacturability. The identified features included in product-tailored test artifacts provide valuable insights about AM manufacturing limitations (constraints) and their interaction with the product's geometry.

The method is structured into six phases, from decomposition of the baseline design to manufacturing of the AM-optimized new design. The first three phases build on previous work by Borgue et al. [21]. In this article, three more phases were included as presented in Figure 1.

1. Functional decomposition: An EF–M model representing the traditionally manufactured product is created.
2. Constraint replacement: Constraints based on traditional manufacturing methods are identified and removed. In their place, AM constraints are introduced into the function model.
3. First redesign for AM: The function model is redesigned for AM. New DSs are developed to replace the previously removed ones. Inactive AM constraints are removed from the model.
4. Prototype manufacturing: Critical geometric features of the design are identified and included in various test artifacts [38] which are then manufactured.
5. Function model improvement and redesign: Lessons learned from the test artifacts are used to improve the AM function model and AM design.
6. Iterative design improvement and manufacturing: Phases 4 and 5 are repeated iteratively.

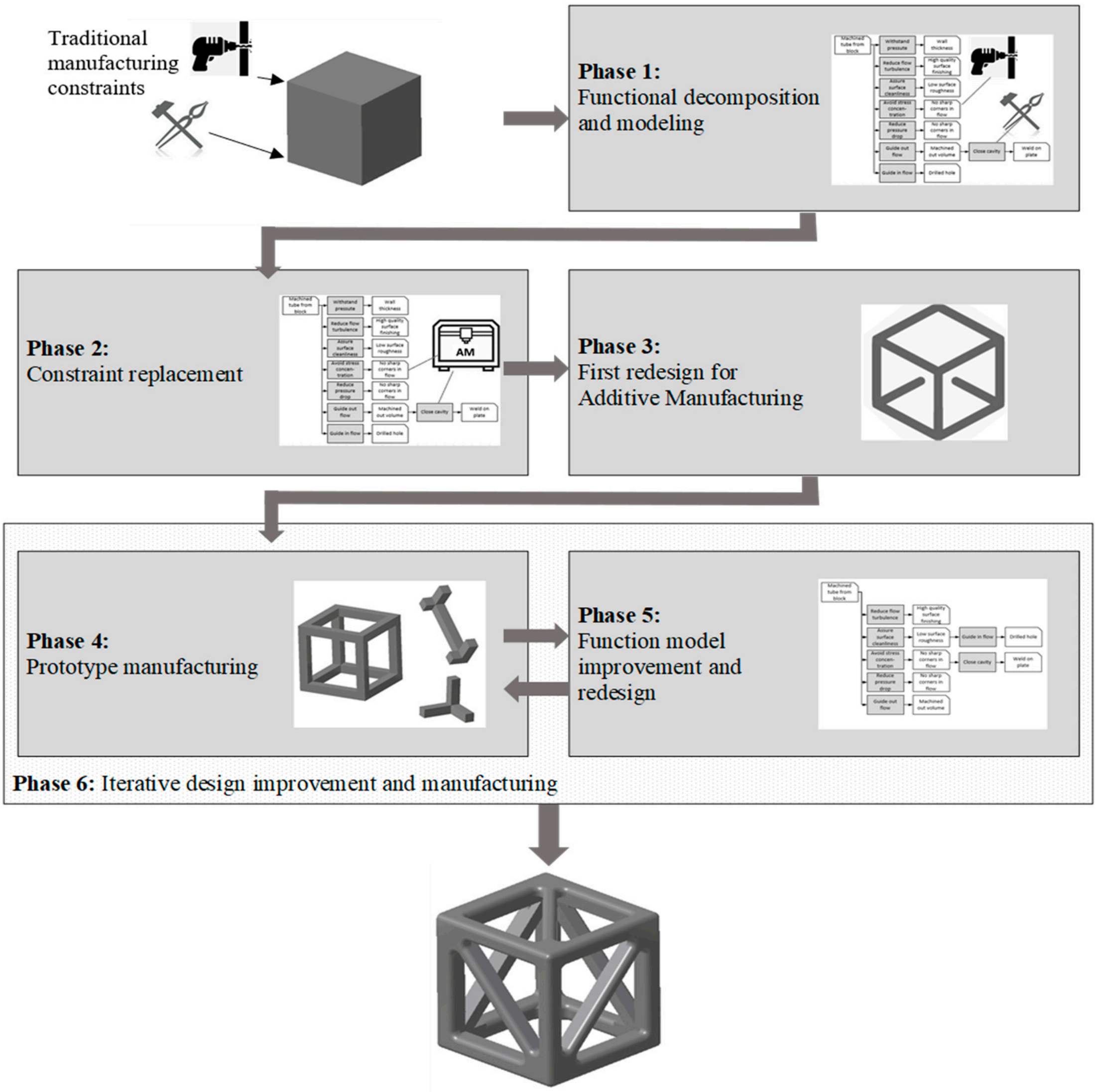


Figure 1. Proposed function model-based design for Additive Manufacturing (DfAM) method. The diagram highlights the iterative process of the prototyping activities.

3.1.1. Phase 1: Functional Decomposition and Modeling

A function tree of the original part is built to facilitate understanding of the product architecture. The function modeling technique EF–M [36] was chosen because it provides a distinct modeling of constraints. However, other modeling strategies are also suitable for functional decomposition such as those proposed by Chesnut [39]; Umeda, Takaeda, and Tomiyama [40]; and Heller and Feldhusen [41].

When implementing the EF–M technique, the part geometry is analyzed to find FRs directly associated to DSs. Then, constraints with an impact on specific DSs are identified and included in the function tree associated with the applicable DS. In the proposed method, a distinction is made between manufacturing constraints (Cms) and functional constraints (Cfs). This is not part of the original EF–M theory but has proven beneficial in a redesign for an AM process [21]. Manufacturing constraints depend on the manufacturing process, such as minimum manufacturable wall thickness, while, in contrast, Cfs depend on FRs such as the maximum pressure a pipe needs to endure. The distinction among constraints facilitates the process of identifying the DSs that are only manufacturing dependent and that can therefore be targeted to be redesigned for AM. To achieve this purpose, configurable components (CCs) are implemented in the function tree as well. These CCs, introduced by Claesson [35], are objects that encapsulate entire branches of related DSs and sub-elements to serve as components in the analysis.

3.1.2. Phase 2: Constraint Replacement

The Cms derived from traditional manufacturing methods and the DSs (and their respective sub-trees) constrained by them are pruned from the function tree. Then, the function model is re-constrained, with AM constraints being introduced to replace those previously removed. For instance, when machining a component, internal cavities cannot be manufactured (as the tool cannot reach them), which leads to the Cm that *Cavities must be reached by tools*. When designing for AM, internal cavities can be manufactured. However, geometries with overhang angles smaller than 45° need support structures [5]. As internal support structures cannot be removed, the Cm that *Cavities must be reached by tools* is then replaced by the AM constraint *Minimum overhang angle, 45°*. At this point, as the AM component has not yet been conceptualized, a general body of AM constraints—general AM guidelines—is considered.

3.1.3. Phase 3: First Redesign for AM

The sub-branches removed in the previous phase open the design space for a new, DfAM-guided design. Other parts of the function model, which are not pruned in this step, provide interfaces and geometry which must be retained. Under consideration of the AM constraints, making use of the explicitly freed up design space, the product is now redesigned. Through this procedure, areas in the function tree that are solely constrained by AM Cms are identified as parts of the product that can be redesigned for AM. Then, a new function tree redesigned for AM is built, and a new product geometry can be conceived. At this point, the focus should be on applying the minimum number of Cms as possible (minimally restrictive constraints [42]) in order to not over-constrain the design space, facilitating AM design freedom while ensuring product manufacturing. Following the definitions established by Patterson and Allison [42] in their design framework for ensuring manufacturability of mechanical components, once AM constraints are identified, they can be classified as active, inactive and unnecessary (IU), inactive and redundant (IR), inactive and internally dominated (IID), or inactive and externally dominated (IIE). Table 1 introduces the terminology for constraint activity according to Patterson and Allison [42].

Table 1. Constraint activity as introduced by Patterson and Allison [42].

Constraint Activity	Characteristics
Active	The constraint restricts the design space (e.g., minimum manufacturable wall thickness).
Inactive and unnecessary (IU)	Other type of constraints (non-manufacturing related) dominate (e.g., internal pressure requirements establish a wall thickness that is thicker than the minimum manufacturable).
Inactive and redundant (IR)	The constraint is identical to others already constraining the design.
Inactive and internally dominated (IID)	The constraint was originally active, but a subsequently imposed Cm rendered it inactive.
Inactive and externally dominated (IIE)	The constraint was originally active, but a subsequently imposed Cf rendered it inactive.

At this point, as manufacturing constraints are geometry-dependent [43], components with different geometries have different active AM constraints in their function model (FM) trees.

3.1.4. Phase 4: Prototype Manufacturing

Additive manufacturing product design must be performed concurrently with studies and analysis of the AM process to be implemented [1,3]. Therefore, studies on the AM process of interest must be closely related to product geometries [27].

In this phase, to assess design manufacturability, the AM manufacturing constraints identified in the previous phases are evaluated [38]. Test artifacts are used to evaluate which manufacturing constraints found in the literature are applicable to the product geometry and AM process implemented. For instance, the minimum overhang angle for support avoidance is known to be 45° [5]; however, this value is a generalization, and the actual minimum overhang depends on material and process parameters [6]. To evaluate manufacturing constraints in the test artifacts, the constraints are parametrized, and the different parameter values evaluated. In a constraint such as minimum overhang angle, the overhang angle is considered a parameter. For its evaluation, geometries with an overhang angle variation from 0 to 45° are manufactured. If machine process setups are also considered a variable parameter, a multiparameter evaluation should be performed following procedures such as design of experiments (DOEs, [44]). The constraint evaluation through test artifacts is complete when the constraint is established, which means that a concrete value is defined for the set of manufacturing process parameters of interest. The importance of distinguishing between active and inactive constraints is highlighted in this phase, as only active constraints are included in the test artifacts.

3.1.5. Phase 5: Function Model Improvement and Redesign

The parametric analysis from Phase 4 provides an accurate understanding of the AM constraints involved in the design. These lessons learned should be documented and introduced in the function model as Cms to systematize and preserve the information. The component is then redesigned according to the improved function tree. In the case of overhangs, test artifacts may have demonstrated that the minimum overhang angle (for the material and process parameters of interest) was less than 45°. In that case, the Cm corresponding to *Minimum overhang angle, 45°* would change, and the design can be changed accordingly. When the component is redesigned, Cms that were inactive in the previous design can become active due to the changes in geometry; these recently active constraints should be included in the FM tree. For example, if an earlier version of the design had attachment holes with a diameter larger than the minimum manufacturable hole, the *Minimum manufacturable hole diameter* was, at that time, an IU Cm. However, if the design changes and the hole diameters are reduced, the Cm *Minimum manufacturable hole diameter* can become active.

3.1.6. Phase 6: Iterative Design Improvement and Manufacturing

If, during the redesign process from Phase 5, new AM constraints become active due to the changes in component geometry, they must be evaluated in test artifacts. If this is the case, Phases 4 and 5 must be repeated until every active manufacturing constraint has been evaluated. When every active manufacturing constraint is established, a new and improved AM design can be manufactured.

3.2. Application of the DfAM Method: Redesign of a Propellant Flow Connector

To illustrate the development of the proposed method, a propellant flow connector for satellite applications was designed. The flow connector was developed to represent significant design features from the three use cases presented at the workshops. Moreover, it was verified in terms of fidelity with industry specialists. The flow connector is a 5 cm tall pipe structure connecting interfaces of different shapes and dimensions that has the main function of guiding fluid with a pressure of 300 bar. Different models of the connector can have from two to six interfaces. One interface corresponds to a vertical circular inlet (1 mm diameter), while the other (up to) five interfaces correspond to horizontal rectangular outlets. Flow connector designs with two to six interfaces are presented in Figure 2.

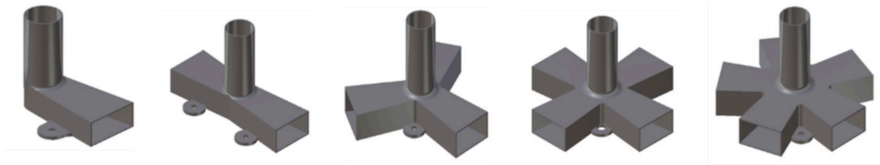


Figure 2. Models of the flow connector can have from two to six interfaces. One interface corresponds to a vertical circular inlet, and the other interfaces correspond to horizontal rectangular outlets.

Currently, the outer shape of the connector was machined from a steel block, the vertical inlet was drilled, and the horizontal outlets were milled from the bottom. The cavity resulting from this process was welded shut with a plate. Afterwards, “ears” for screwing the connector onto the satellite were integrated into the product. In this case study, the flow connector was redesigned to be manufactured with AM LPBF.

3.2.1. Functional Decomposition

As detailed in Section 3.1, the first step in the redesign process was a functional decomposition. During this procedure, FRs, DSs, and Cs were identified by an expert panel. Then, those FRs, DSs, and Cs were organized in a hierarchical function tree, as shown in Figure 3, where DSs were connected with other DSs through “iw” connections and Cs through “icb” connections. More details about this process can be found in previous work by Borgue et al. [21].

Lastly, the function tree was encapsulated into different CCs (tube, outlet, inlet, and satellite interfaces) to ease the identification and substitution process as shown in Figure 3.

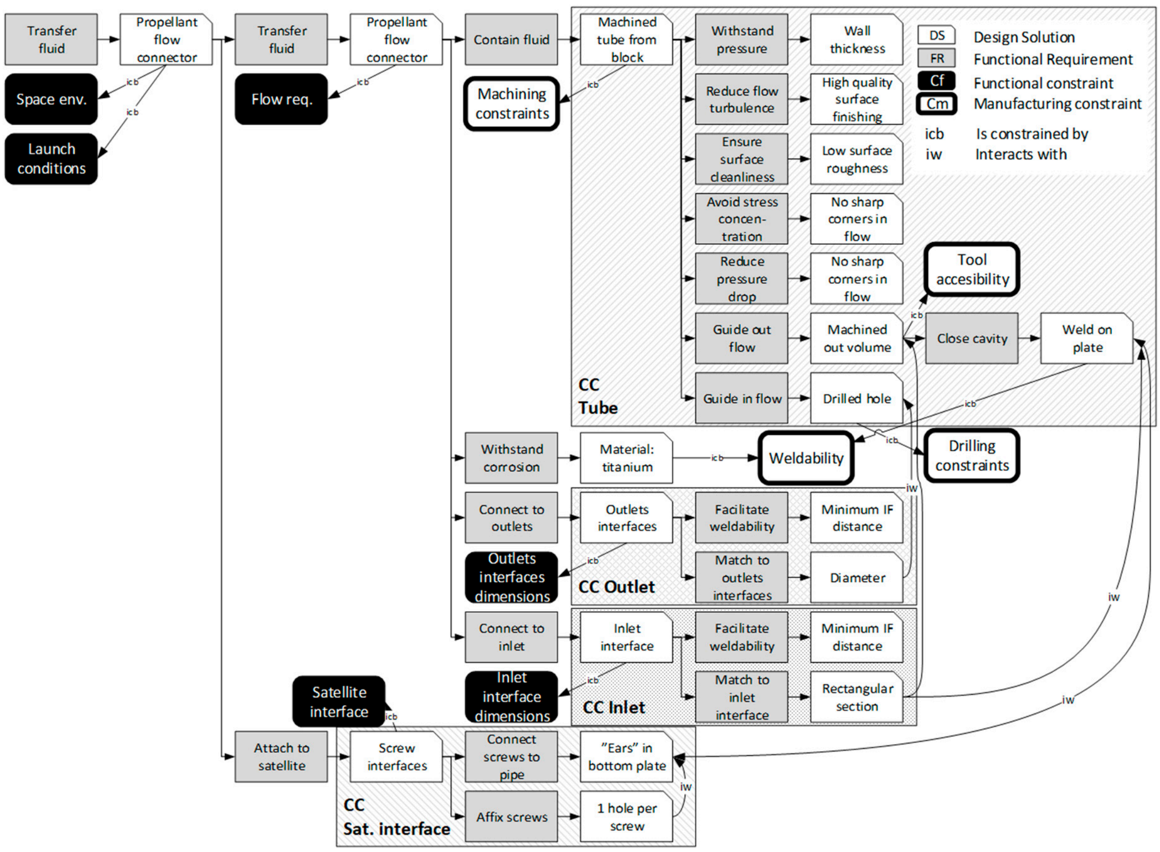


Figure 3. Functional decomposition of the propellant flow connector. The “iw” and “ipmb” connectors were only modeled to the extent needed for the demonstration to keep the graph readable.

3.2.2. Constraint Replacement

Captured in the function model in Figure 3 are both Cfs and Cms. Since the welded connection with the system level (inlet and outlets) cannot be changed, the respective Cm was retained. However, due to the change in manufacturing methods (from machining to AM), the Cm *Machining constraints* for the CC *Tube* was removed. Its removal frees the design space for the entire CC *Tube*. Moreover, due to the "iw" connection from the DS *Weld on plate* in the CC *Tube* to the DS *"Ears" in bottom plate* in the CC *Satellite interface*, the CC *Satellite interface* was affected by the design change as well and could be redesigned.

To replace the traditional manufacturing constraints with appropriate AM constraints, LPBF constraints were obtained from the European Powder Metallurgic Association [5]; these are presented in Table 2. Due to the reduced size of the propellant flow connector, constraints such as the maximum building volume or the maximum channel diameter (10 mm) to avoid support structures were not considered in the analysis.

Table 2. The Additive Manufacturing (AM) laser powder-bed fusion (LPBF) constraints relevant for the manufacturing process of the propellant flow connector [5].

Constraints	Regards
Building orientation	Surfaces facing down in the building plate (down skin) should be those able to be machined afterwards for improved surface roughness. Their thickness must be increased to account for the portion to be machined out.
Removal of support structures	Orient part to ease support removal.
Reduce support structures	Overhang angle > 45°.
Enable heat dissipation	Avoid "thin to thick" geometries placed in the vertical direction of the building machine. The heat generated by the laser beam does not have a "path" in the part to evacuate quickly, with detrimental consequences on surface roughness.
Hole definition	Holes below 0.4 mm are not feasible both because of powder removal and the possible occurrence of consolidation between the top and bottom of the hole.

3.2.3. Component Redesign for AM

After the CC *Tube* design space was freed, the DS *Machined tube from block* was removed and replaced by the *AM Tube*, which was constrained by the Cm *LPBF constraints*. Table 2 lists the LPBF manufacturing constraints. Making use of the wider design freedom in AM, a new design based on physics models was created for the tube part. The design takes the form of a curved connector shape with a continuous change in cross-section which reduces fluid resistance. This shape connects inlet and outlet interfaces while minimizing the energy loss of the fluid [45]. The FR and DS in the CC *AM Tube* and *Satellite interface* are illustrated in Figure 4. Based on the previously discussed AM constraints, the DS *Wall thickness* was constrained by *Minimum wall thickness*. At the same time, the DS *Hydrodynamically optimized shape* was constrained by *Overhang angle > 45°*, *Thickness ratio (vertical)*, *Thicker down skins*, and the *Maximum height-to-diameter ratio*. As the inlet was connected to one or more outputs, the DS *AM progressive shape* was constrained by *Minimum distance between outlets*. This latest constraint followed the same principle of the minimum diameter for AM holes. If the distance between outlets is too narrow, powder particles can be trapped in between, which can generate surface defects.

The connectors for attaching the propellant tube to the satellite interface were integrated into the tube structure and were also redesigned as the DS *Connector support*. *Connector support* was constrained by the LPBF constraints *Minimum wall thickness*, *Thicker down skins*, *Thickness ratio (vertical)*, and *Flatness*.

The DS *Affix screws* was constrained by *Cylindricity*. Figure 4 presents the CC *AM Tube* and CC *Satellite interface* for the redesigned connector model next to the redesigned geometry and build orientation. As CC *Inlet* and CC *Outlet* were not redesigned, they are not included in Figure 4. In the proposed component design, there were no holes with diameters below 0.4 mm; for this reason, this constraint was not further considered in the FM analysis (the constraint was IU).

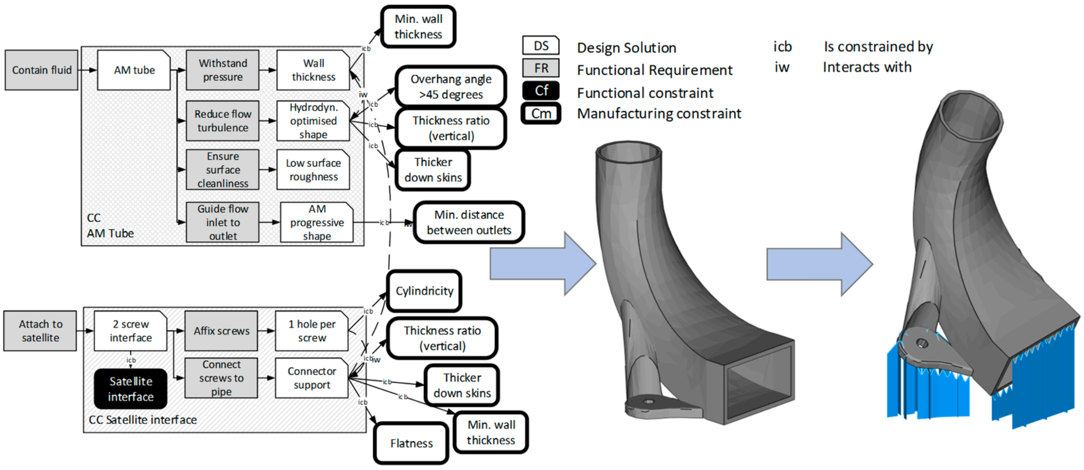


Figure 4. Propellant flow connector redesigned for AM presenting the preferred build orientation and the support structures generated for its manufacturing. The configurable components (CCs) *AM Tube* and *Satellite interface* depict how the AM constraints are modeled in the AM tree.

3.2.4. Prototyping

Additive manufacturing powder bed processes are based on complex physical phenomena, and AM manufacturing constraints are largely geometry dependent [43]. For this reason, each manufacturing constraint obtained from the literature must be evaluated for the product geometry of interest. However, several manufacturing constraints can be evaluated in the same test artifact as exhibited in Figure 5. Figure 5 presents the three types of test artifacts chosen to evaluate the manufacturing constraints obtained from the literature in respect to the product geometry. In this case, due to the reduced size of the flow connector, it was possible to manufacture its entirety as one of the test artifacts to assess the constraints *Thickness ratio (Vertical)*, *Thicker down skins*, *Flatness*, and *Cylindricity*. This test artifact had one inlet and one outlet and was printed in the same printing direction as a final product with one outlet would have.

The constraint *Thicker down skins* was translated into a 1 mm thicker connector support bottom. The constraint *Minimum wall thickness* was evaluated with the constraint *Cylindricity* using tubes with different wall thicknesses. The constraint *Minimum distance between outlets* was evaluated with test artifacts that were similar in appearance to an open book to assess how close the "book leaves" can be without observing defects between them. Moreover, the book-like test artifacts were printed in various orientations to observe how the orientation in the AM machine influences defect generation. These results shed light on the possible printing orientations of flow connectors with more than one outlet.

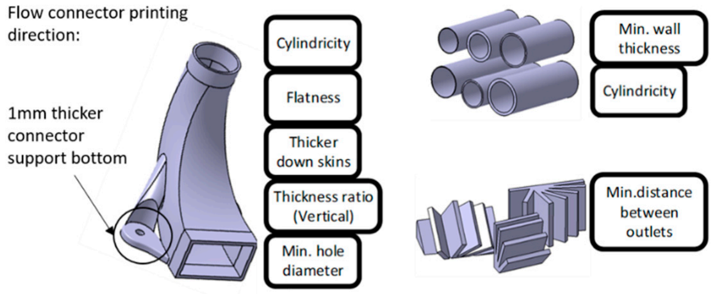


Figure 5. Test artifacts to assess LPBF manufacturing constraints in relation to the flow connector geometry.

Figure 6 shows the test artifacts that were manufactured with a LPBF machine (from Electro Optical Systems (EOS), GmbH, Munich, Germany) EOS M290 equipped with a Yb-fiber laser. The feedstock material was a gas-atomized stainless steel 316L powder with particle size distribution of 20–53 µm. The artifacts were fabricated utilizing standard process parameters provided by EOS. These parameters included a strip scanning strategy with a 67° rotation and contour scanning as described in detail by Leicht, Klement, and Hryha [46]. The parameters were optimized for high density, low surface roughness, and high dimensional accuracy, and they adjusted automatically for different design features such as up and down skins. These sets of parameters were used for the manufacturing process of the final product as well. Figure 6a exhibits the flow connector after removal from the build plate without any post-treatment. In Figure 6b,c, the support structures were removed, the part was sandblasted, and 1 mm of the connector support bottom was machined out. However, it can be noted in Figure 6c that surface defects persisted and that more material must be machined out to improve surface quality. Moreover, as the ears (for connecting to the satellite) were separated from each other (Figure 6c) and the post-processing activities in this case were manual, there was a risk of having an uneven flow connector bottom after post-processing.

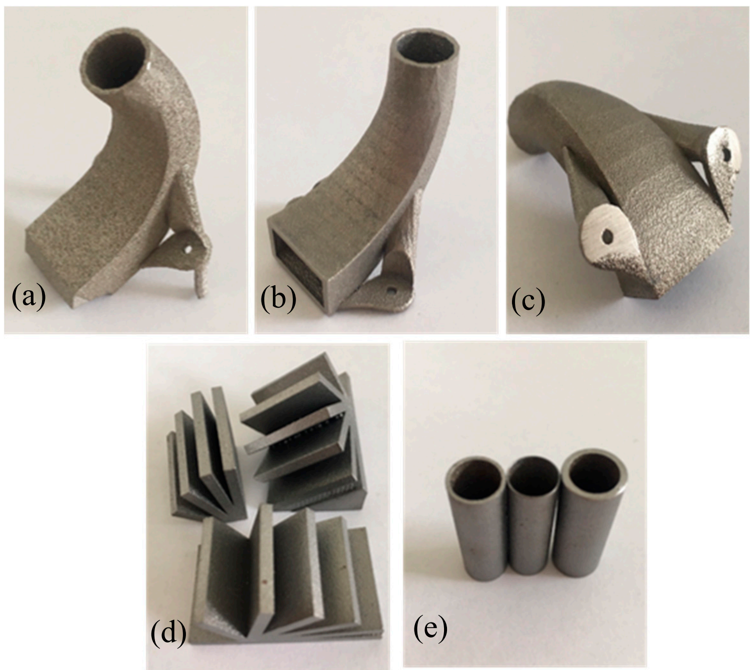


Figure 6. (**a**) Flow connector with support structures; (**b**) flow connector without support structures; (**c**) flow connector underside; after the removal of a 1 mm layer of material, the surface defects persisted; (**d**) separation between outlets should be larger than 30° to avoid the generation of defects among the outlets; (**e**) no manufacturing defects were observed in the pipe-like test artifacts.

The most convenient way to remove the support structures generated in the outlet was to cut a large portion of the outlet structure. This process eliminated 3 mm of the outlet interface, the length which serves for connecting the flow connector to other devices.

The book-like test artifacts (Figure 6d) show that the separation among outlets should be greater than 30° to avoid an inferior surface roughness and dimensions among the outlets; below 30°, the presence of unmelted particles on the outlet surfaces was observed. Moreover, on certain building orientations, support structures among the leaves were observed, as the overhang angle was too low.

The pipe-like test artifacts (Figure 6e) were manufactured with an 8:1 height-to-diameter ratio and wall thicknesses from 0.2 to 1 mm to test the connector's structural stability. The parts were all successfully manufactured without any build failures. Furthermore, based on visual inspection, it seems that the presented design had a high manufacturing quality.

3.2.5. Function Model Improvement and Redesign

Based on the results obtained from the test artifacts, several constraints were updated and others created. Table 3 summarizes the lessons learned from the prototyping activities.

- To remove the support structures from the connector outlet, 3 mm of the outlet length was cut off. A new constraint (*Length + 3 mm*) was added to the DS *Minimum IF distance*.
- As the support removal procedure is manual, complying with the constraint *Flatness* was problematic while having two separated ears. For this reason, the constraint *Joined bottom* was included for the DS *Connector support*.
- To ensure the complete removal of the rough down facing surface, the constraint *Thicker down skin* was replaced by *Thickness + 2 mm* in the DS *Connector support*.
- From the results of the pipe-like test artifacts, the constraint *Minimum wall thickness* was established as *Minimum wall thickness = 0.2 mm*.
- The results from the book-like test artifacts suggested the creation of the constraint *Minimum outlet separation = 30°*.
- The sole evaluation performed regarding the constraint *Thickness ratio (Vertical)* was to determine whether the current design presented rough surfaces due to the poor heat dissipation. As the features implemented in the design seemed to avoid this phenomenon, this constraint remained unchanged.

Table 3. Lessons learned from the prototyping activities.

Constraint	Status	Comments	Action
Thickness ratio (Vertical)	Unchanged	No observable surface defects due to the poor heat dissipation	-
Thicker down skins	Updated	Surface defects persisting after removing a 1 mm layer	Change to *Thickness + 2 mm*
Flatness	Unchanged	Problematic to ensure with current design	Introduce new constraint *Joined bottom*
Minimum wall thickness	Updated	No observable defects from pipe-like test artifacts	Change to *Minimum wall thickness = 0.2 mm*
Length + 3 mm	New	Created to ensure outlet weldability after support removal	-
Joined bottom	New	Created to facilitate bottom flatness	-
Minimum outlet separation = 30°	New	Created to avoid the generation of unmelted particles between outlets	-

The previously mentioned changes in the manufacturing constraints were introduced in the function model presented in Figure 7.

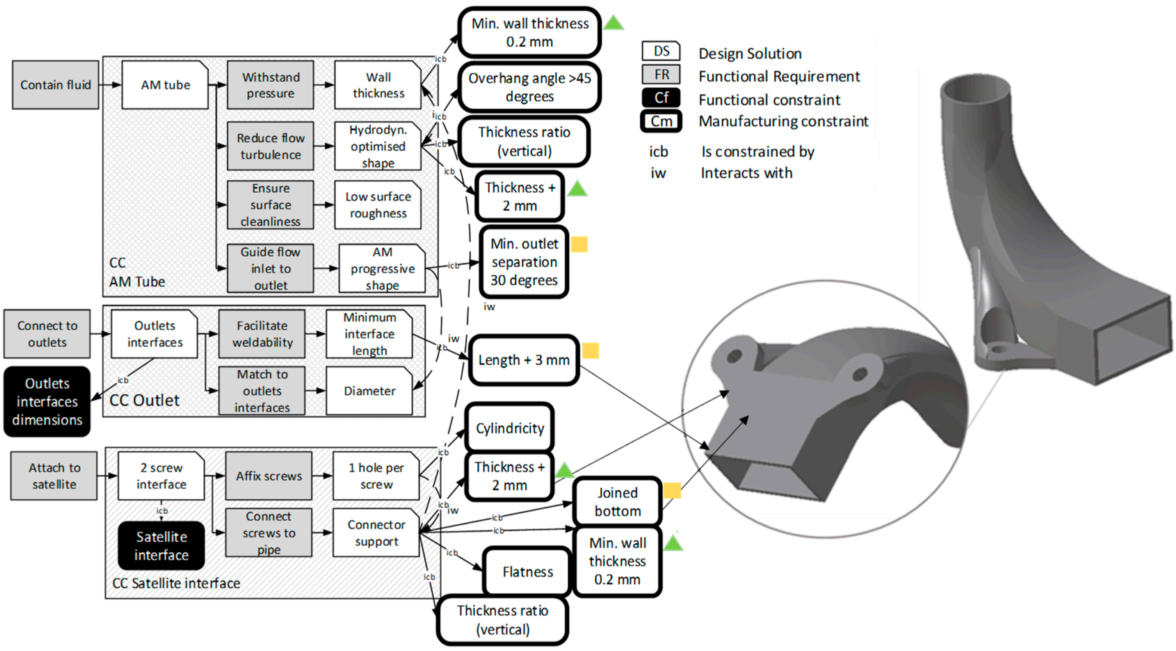


Figure 7. Redesigned FM tree after prototyping activities. The green arrows indicate constraints that have been updated, and the orange squares indicate new constraints.

3.2.6. Iterative Design Improvement

After updating the function model with updated and new manufacturing constraints, a new propellant flow connector implementing the same AM machine and process parameters used for the prototypes was manufactured. The new propellant flow connector is presented in Figure 8. The design has a joined bottom and, as the outlet length (to compensate for the removal of support structures) and the connector support thickness were extended in the design, the outcome was a connector with a weldable outlet and a smooth bottom. As the manufacturing of the second flow connector was successful, no other changes in the component geometry were required, and every AM constraint was established as suggested in Table 4. Therefore, there was no need to continue the prototyping activities and design iterations.

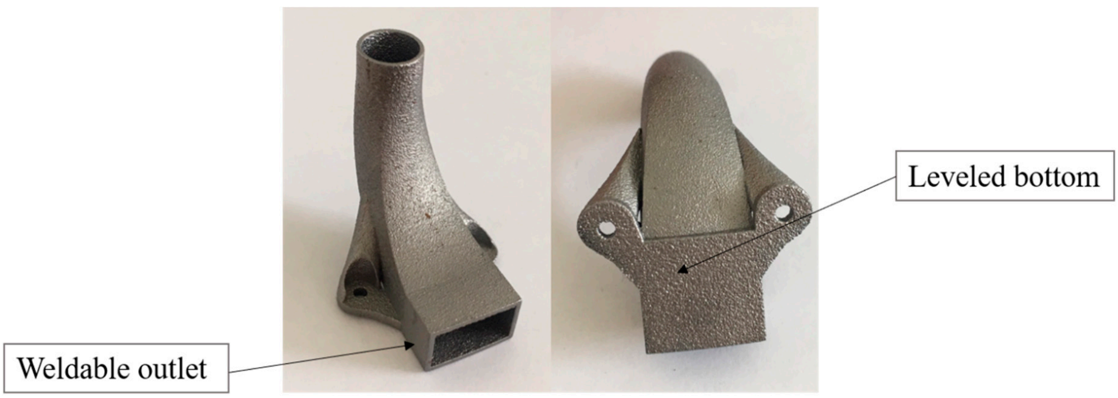


Figure 8. Final propellant flow connector design manufactured with AM LPBF.

Table 4. AM constraints established after prototyping activities.

Constraint	Status	Comments	Action
Thickness ratio (Vertical)	Established	No observable surface defects due to the poor heat dissipation	-
Thickness + 2 mm	Established	No observable surface defects after removing a 2 mm layer	-
Flatness	Established	Ensured with current "joined bottom" design	-
Minimum wall thickness = 0.2 mm	Established	No observable defects from the pipe-like test artifacts	-
Length + 3 mm	Established	Ensured weldability after support removal	-
Joined bottom	Established	Facilitates bottom flatness	-
Minimum outlet separation = 30°	Established	No observable unmelted particles between outlets	-

4. Discussion

In this article, a DfAM method intended to support designers in considering how manufacturing processes and material properties influence product design was proposed. The method is based on refining the general AM design guidelines found in the literature [5] to make them relevant for a specific product development project and the respective AM parameters of interest. The AM design guidelines are represented in relation to the product's function structure in the form of manufacturing constraints. This representation is made by implementing the EF–M function modeling technique. As manufacturing constraints are dependent on various process parameters (such as the material used, machine setups, and geometry [3]), the constraints obtained from the literature need to be adapted for the product to be designed. This is done through the manufacturing of test artifacts. The literature on the development of AM test artifacts is vast [26]; however, there is a lack of methodologies for selecting test artifacts based on product features. The modeling approach proposed in this paper is intended to support designers in evaluating the manufacturability of specific product features, thereby contributing to shorter development times and time to market. One of the latest methodologies for test artifact design based on product features was proposed by Rupal, Ahmad, and Qureshi [27] and Rupal, Secanell, and Qureshi [28], where product-critical features were identified and included in AM test artifacts. The method presented in this article takes this procedure one step forward by utilizing the results from the test artifacts to iteratively improve the design of a product and ensure its manufacturability and quality. Moreover, studies conducted by authors such as Booth et al. [47] highlight the need for establishing process- and product-specific guidelines to accurately account for the unique limitations of each AM process. Implementing product-tailored design artifacts supports the development of a knowledge database or design guideline adapted to a specific product and AM process.

In this article, the test artifacts were specifically designed based on the constraints and geometry features available in the product in correlation with the machinery, material, and manufacturing parameters used. The results from these test artifacts were reintroduced into the function model, where they were used to update previous constraints or even create new ones. Therefore, the function model acts as a model-based database for product and manufacturing process information which can be reused to further develop a product or product family and increase AM-documented knowledge. Similar development of product families based on EF–M models has been described by Johannesson and

Claesson [37]. Function modeling and the carryover of the DfAM constraints in such a scenario allow for continuous knowledge capture and development. Moreover, a model-based database that includes both conceptual design information (DSs) and manufacturing information (Cms) has the potential to act as a boundary object [48,49] between manufacturing and design teams. Experts' manufacturing knowledge (perhaps tacit) can be documented in the model with ease and communicated to designers or less experienced engineers thus facilitating communication and coordination efforts that could further reduce development time and costs. Furthermore, as AM constraints are machine-dependent, early constraint modeling efforts can support decision-making procedures concerning future machine purchases and technology development activities.

The function model supports the distinction between active and inactive manufacturing constraints. The identification of active constraints reduces and clarifies the geometrical features to be tested in design artifacts. In the case study, for instance, when the machining constraints were replaced by AM constraints (before the first AM redesign was created), the minimum manufacturable AM hole (0.4 mm diameter) was considered an active constraint. However, as the AM flow connector did not have such small holes or pockets, that constraint became IU and was not included in the test artifacts. This distinction and the results it enabled resonate well with the work of authors such as Patterson and Allison [42] where distinguishing between active and inactive constraints facilitated the design of manufacturable components while imposing as few restrictions on the design space as possible (minimally constrained). Table 1, in Section 3.1, presents five constraint distinctions (active, IU, IR, IID, and IIE, [42]). However, due to the simplicity of the case study developed in this article, only the use of active and IU constraints were evidenced. Moreover, as the case study was conducted for illustrative purposes, the AM active constraints identified and tested in the case study were not a complete set of active manufacturing constraints for the flow connector. Furthermore, no verification or validation was conducted to be able to confirm that the identified constraints and their distinction (active or inactive) were accurate.

In a real design scenario, during long design processes for complex or critical products, it may be possible to identify a larger number of active Cms. However, in such a scenario, the implementation of the five constraint distinctions is recommended, as some manufacturing constraints might be overridden by other design requirements such as fatigue response, material specifications, or cost limitations. Regarding active and inactive constraints, their identification starts concurrently with the design conceptualization with assumptions being based on previous design experience. The iterative nature of the proposed method nevertheless facilitates the continuous identification and distinction of constraints thus providing the possibility of reevaluating previous assumptions. Furthermore, the documentation ability provided by the function model can be an advantage when identifying and distinguishing constraints in future design projects.

The proposed product-tailored test artifacts contribute to ensure component manufacturability which has the potential of reducing costs for development, manufacturing, and, later in the product development process, qualification activities. Moreover, product-tailored AM test artifacts contribute to reducing material consumption and prototyping costs [27].

The presented method emerges from an empirical study performed through workshops with industrial practitioners from three different space component manufacturers. A main reflection reported by the industrial practitioners is that the AM product design must be performed concurrently with the analysis of the AM manufacturing processes and especially on the ways that such process parameters interact with the product geometry. Such reflections are in accordance with the literature (e.g., [1]). Moreover, the workshop participants recognized that, at present, DfAM design experience is limited, and the extensive literature on AM processes is not entirely applicable for specific geometries, machines, and process setups. General AM design guidelines must be refined and re-evaluated through test artifacts. These results resonate well with those presented by authors such as Rebaioli and Fassi [26]; Rupal, Ahmad, and Qureshi [27]; and Rupal, Secanell, and Qureshi [28] who focus their work on the design of AM test artifacts.

In the case study, AM constraints were identified and evaluated based on product geometry and process parameters. To ensure reliable, repeatable, and structured results, implementing techniques, such as DOEs [44], are considered for a future extension of the presented method. The use of these techniques has proven to be a reliable and efficient strategy for optimizing testing activities in the aerospace sector [50]. Currently, research on how process parameters impact product quality is scarce [51]. However, several authors have addressed this knowledge gap with the implementation of various DOE techniques, such as central composite design [51], half-factorial design [52], or Taguchi methods [53].

When evaluating the minimum distance between outlets, for instance, a DOE can be established for the parameters *angle between outlets* and *building orientation*. In the presented method, a DOE technique was not applied but is considered a promising extension of the method.

The method proposed in this paper requires a certain degree of abstraction and formalism which often implies additional efforts by designers and the organization in general. However, there are some considerations that motivate such an increased degree of formalism:

1. In an aerospace organization, design and testing are normally conducted by different departments or even by different companies. The proposed method can facilitate iterative efforts between design and testing activities to assess how manufacturing processes and material properties influence product design and product quality [1].
2. Additive manufacturing capabilities are maturing (and improving), and there could be a need to capture such a level of maturity over time. Introducing this formalism can facilitate the management of knowledge regarding manufacturing constraints.

5. Conclusions

To support designers in making use of AM design freedom while ensuring product manufacturability, a DfAM method was presented. The method is based on the main assumption that the lessons learned from testing and prototyping activities can be systematically captured and organized to support design activities. To enable this capturing, this study introduced a DfAM method in which a representation often used in early design, a function–means model, was extended with the introduction of a new model construct, Cm. In this approach, the association between AM Cms and DSs was made by the concurrent testing of tailored test artifacts based on the design scenario of interest.

The method was applied to the redesign, manufacturing, and testing of a flow connector for a satellite. The application in this case study illustrates how the method can be used as a cost-efficient method to challenge the general AM design guidelines found in the literature and as a means to redefine and update manufacturing constraints. Furthermore, the DfAM method can be used to document and manipulate the associations between product functions, DSs, and AM manufacturing constraints thus providing the basis for a manufacturing constraints database to be used for future designs. This can contribute to the effective increase in the AM knowledge inside an aerospace organization, thereby shortening future products' development times and costs.

Author Contributions: Conceptualization, O.B. and J.M.; Formal analysis, O.B., J.M. and A.L.; Funding acquisition, O.I.; Investigation, O.B., J.M., M.P. and O.I.; Methodology, O.B. and J.M.; Resources, A.L.; Supervision, M.P. and O.I.; Visualization, O.B.; Writing—original draft, O.B.; Writing—review & editing, J.M., A.L., M.P. and O.I.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. O'Brien, M.J. Development and qualification of additively manufactured parts for space. In *Laser 3D Manufacturing V*; International Society for Optics and Photonics (SPIE): Bellingham, WA, USA, 2018; pp. 1–14.
2. Di Caprio, F.; Acanfora, V.; Franchitti, S.; Sellitto, A.; Riccio, A. Hybrid metal/composite lattice structures: Design for additive manufacturing. *Aerospace* **2019**, *6*, 71. [CrossRef]
3. Leicht, A. Aspects of Building Geometry and Powder Characteristics in Powder Bed Fusion. Ph.D. Thesis, Chalmers University of Technology, Göteborg, Sweden, 2018.
4. Thompson, M.; Moroni, G.; Vaneker, T.; Fadel, G.; Campbell, R.; Gibson, I.; Martina, F. Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Ann.* **2016**, *65*, 737–760. [CrossRef]
5. European Powder Metallurgy Association (EPMA). *Introduction to Additive Manufacturing Technology—A Guide for Designers and Engineers*; EPMA: Shrewsbury, UK, 2019; Available online: https://www.epma.com/epma-free-publications (accessed on 28 September 2019).
6. Jiang, J.; Stringer, J.; Xu, X.; Zhong, R.Y. Investigation of printable threshold overhang angle in extrusion-based additive manufacturing for reducing support waste. *Int. J. Comput. Integr. Manuf.* **2018**, *31*, 961–969. [CrossRef]
7. Castet, J.; Saleh, J. Satellite reliability: Statistical data analysis and modeling. *J. Spacecr. Rocket.* **2019**, *46*, 1065–1076. [CrossRef]
8. Gibson, I.; Rosen, D.W.; Stucker, B. *Additive Manufacturing Technologies—Rapid Prototyping to Direct Digital Manufacturing*; Springer: New York, NY, USA, 2010.
9. Gausemeie, J.; Echterhoff, N.; Wall, M. *Thinking Ahead the Future of Additive Manufacturing—Innovation Roadmapping of Required Advancements*; University of Paderborn: Paderborn, Germany, 2013.
10. Dordlofva, C.; Borgue, O.; Panarotto, M.; Isaksson, O. Drivers and guidelines in design for qualification using additive manufacturing in space applications. In Proceedings of the International Conference on Engineering Design (ICED 19), Delft, The Netherlands, 4–9 August 2019.
11. Eisenbart, B.; Gericke, K.; Blessing, L. An analysis of functional modeling approaches across disciplines. *AI EDAM* **2013**, *27*, 281–289. [CrossRef]
12. Eisenbart, B.; Gericke, K.; Blessing, L.T. Taking a look at the utilisation of function models in interdisciplinary design: Insights from ten engineering companies. *Res. Eng. Des.* **2017**, *28*, 299–331. [CrossRef]
13. McInnes, A.I.; Harps, D.; Lang, J.; Swenson, C.M. A systems engineering tool for satellite simulator design. In Proceedings of the ASME 2010 10th Biennial Conference on Engineering Systems Design and Analysis, Istanbul, Turkey, 12–14 July 2010. [CrossRef]
14. Boudjemai, A.; Bekhti, M.; Bouanane, M.H.; Si Mohammed, A.M.; Cooper, G.; Richardson, G. Small satellite computer aided design and manfacturing. In Proceedings of the European Conference on Spacecraft Structures, Materials & Mechanical Testing, Noordwijk, The Netherlands, 10–12 May 2005.
15. Quincieu, J.; Robinson, C.; Stucker, B.; Mosher, T. Case study: Selective laser sintering of the USUSat II small satellite structure. *Assem. Autom.* **2015**, *25*, 267–272. [CrossRef]
16. Boschetto, A.; Bottini, L.; Eugeni, M.; Cardini, V.; Nisi, G.G.; Veniali, F.; Gaudenzi, P. Selective laser melting of a 1U cubesat structure. Design for additive manufacturing and assembly. *Acta Astronaut.* **2019**, *159*, 377–384. [CrossRef]
17. Boyard, N.; Rivette, M.; Christmann, O.; Richir, S. A design methodology for parts using additive manufacturing. In Proceedings of the International Conference on Advanced Research in Virtual and Rapid Prototyping VRAP, Leiria, Portugal, 1–5 October 2013; pp. 399–404. [CrossRef]
18. Campbell, I.; Bourell, D.; Gibson, I. Additive manufacturing: Rapid prototyping comes of age. *Rapid Prototyp. J.* **2012**, *18*, 255–258. [CrossRef]
19. Orme, M.E.; Gschweitl, M.; Vernon, R.; Ferrari, M.; Madera, I.J.; Yancey, R.; Mouriaux, F. A demonstration of additive manufacturing as an enabling technology for rapid satellite design and fabrication. In Proceedings of the International SAMPE Technical Conference, Long Beach, CA, USA, 23–26 May 2016.
20. Thornton, J.; Dalay, B.; Smith, D. Additive manufacturing of waveguide for Ku-band satellite communications antenna. In Proceedings of the 2016 10th European Conference on Antennas and Propagation, Davos, Switzerland, 10–15 April 2016.

21. Borgue, O.; Panarotto, M.; Isaksson, O. Impact on design when introducing additive manufacturing in space applications. In Proceedings of the 15th International Design Conference, Dubrovnik, Croatia, 21–24 May 2018; pp. 997–1008. [CrossRef]
22. Booth, P.; Skeen, M.; Stirland, S. Low cost, short lead-time feed chain components for multi-beam antennas. In Proceedings of the European Conference on Antennas and Propagation, Berlin, Germany, 23–27 March 2009.
23. Guo, N.; Leu, M.C. Additive manufacturing: Technology, applications and research needs. *Front. Mech. Eng.* **2013**, *8*, 215–243. [CrossRef]
24. Frazier, W.E. Metal additive manufacturing: A review. *J. Mater. Eng. Perform.* **2014**, *23*, 1917–1928. [CrossRef]
25. Sames, W.J.; List, F.A.; Pannala, S.; Dehoff, R.R.; Babu, S.S. The metallurgy and processing science of metal additive manufacturing. *Int. Mater. Rev.* **2016**, *61*, 315–360. [CrossRef]
26. Rebaioli, L.; Fassi, I. A review on benchmark artifacts for evaluating the geometric performance of additive manufacturing processes. *Int. J. Adv. Manuf. Technol.* **2017**, *93*, 2571–2598. [CrossRef]
27. Rupal, B.S.; Ahmad, R.; Qureshi, A.J. Feature-based methodology for design of geometric benchmark test artifacts for additive manufacturing processes. *Procedia CIRP* **2018**, *70*, 84–89. [CrossRef]
28. Rupal, B.S.; Secanell, M.; Qureshi, A.J. Geometric benchmark test artifact for laser powder bed fusion process: Design and preliminary results. In Proceedings of the 2nd Conference of NSERC Network for Holistic Innovation in Additive Manufacturing (HI-AM), Vancouver, BC, Canada, 26–27 June 2019.
29. Gerling, W.H.; Preussger, A.; Wulfert, F.W. Reliability qualification of semiconductor devices based on physics-of-failure and risk and opportunity assessment. *Qual. Reliab. Eng. Int.* **2002**, *18*, 81–98. [CrossRef]
30. Avison, D.; Lau, F.; Myers, M.; Nielsen, P. Action research. *Mag. Commun. ACM* **1999**, *42*, 94–97. [CrossRef]
31. Lindwall, A.; Törlind, P. Evaluating design heuristics for additive manufacturing as an explorative workshop method. In Proceedings of the 15th International Design Conference, Dubrovnik, Croatia, 21–24 May 2018; pp. 1221–1232.
32. Cross, N. *Engineering Design Methods*; John Wiley and Sons Ltd.: Chichester, UK, 2000.
33. Levandowski, C.E.; Corin-Stig, D.; Bergsjö, D.; Forslund, A.; Högman, U.; Söderberg, R.; Johannesson, H. An integrated approach to technology platform and product platform development. *Concurr. Eng.* **2013**, *21*, 65–83. [CrossRef]
34. Landahl, J.; Panarotto, M.; Johannesson, H.; Isaksson, O.; Lööf, J. Towards adopting digital twins to support design reuse during platform concept development. In Proceedings of the NordDesign 2018, Linköping, Sweden, 14–17 August 2018.
35. Claesson, A. A Configurable Component Framework Supporting Platform-Based Product Development. Ph.D. Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2006.
36. Miles, M.B.; Huberman, A.M. *Qualitative Data Analysis: An Expanded Sourcebook*; Sage Publications: Beverly Hills, CA, USA, 1994.
37. Johannesson, H.; Claesson, A. Systematic product platform design: A combined function-means and parametric modeling approach. *J. Eng. Des.* **2005**, *16*, 25–43. [CrossRef]
38. Dordlofva, C.; Törlind, P. Design for qualification: A process for developing additive manufacturing components for critical systems. In Proceedings of the NordDesign 2018, Linköping, Sweden, 14–17 August 2018.
39. Chestnut, H. *Systems Engineering Methods*; Wiley: New York, NY, USA; London, UK; Sydney, Australia, 1967.
40. Umeda, Y.; Takeda, H.; Tomiyama, T. Function, behaviour and structure. In *Applications of Artificial Intelligence in Engineering*; Springer: Berlin, Germany, 1990; pp. 177–194.
41. Heller, J.; Feldhusen, J. Enhanced function structure applicability through adaptive function templates. In Proceedings of the ATINER'S Conference, Athens, Greece, 10–13 June 2013.
42. Patterson, A.; Allison, J. Generation and mapping of minimally-restrictive manufacturability constraints for mechanical design problems. In Proceedings of the 24th Design for Manufacturing and the Life Cycle Conference (DFMLC)—ASME IDETC/CIE, Anaheim, CA, USA, 18–21 August 2019.
43. Meier, C.; Penny, R.W.; Zou, Y.; Gibbs, J.S.; Hart, A.J. Thermophysical phenomena in metal additive manufacturing by selective laser melting: Fundamentals, modeling, simulation and experimentation. *arXiv* **2017**, arXiv:1709.09510. [CrossRef]
44. Antony, J. *Design of Experiments for Engineers and Scientists*; Elsevier: Amsterdam, The Netherlands, 2014.

45. Fox, R.; McDonald, A.; Pritchard, P. *Introduction to Fluid Mechanics*, 6th ed.; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2006.
46. Leicht, A.; Klement, U.; Hryha, E. Effect of build geometry on the microstructural development of 316L parts produced by additive manufacturing. *Mater. Charact.* **2018**, *143*, 137–143. [CrossRef]
47. Booth, J.; Alperovich, J.; Ma, J.; Reid, T.; Ramani, K. The design for additive manufacturing worksheet. *J. Mech. Des.* **2017**, *139*, 100904. [CrossRef]
48. Star, S.L. The structure of ill-structured solutions: Heterogeneous problem-solving, boundary objects and distributed artificial intelligence. *Distrib. Artif. Intell.* **1989**, *2*, 37–54.
49. Subrahmanian, E.; Monarch, I.; Konda, S.; Granger, H.; Milliken, R.; Westerberg, A. Boundary objects and prototypes at the interfaces of engineering design. *Comput. Support. Coop. Work* **2003**, *12*, 185–203. [CrossRef]
50. Madrid, J.; Lorin, S.; Söderberg, R.; Hammersberg, P.; Wärmefjord, K.; Lööf, J. A virtual design of experiments method to evaluate the effect of design and welding parameters on weld quality in aerospace applications. *Aerospace* **2019**, *6*, 74. [CrossRef]
51. Equbal, A.; Equbal, M.A.; Equbal, M.I.; Sood, A.K. Multi-criterion decision method for roughness optimization of fused deposition modelled parts. In *Additive Manufacturing Technologies from an Optimization Perspective*; IGI Global: Hershey, PA, USA, 2019; pp. 235–262.
52. Pérez, M.; Medina-Sánchez, G.; García-Collado, A.; Gupta, M.; Carou, D. Surface quality enhancement of fused deposition modeling (FDM) printed samples based on the selection of critical printing parameters. *Materials* **2018**, *11*, 1382. [CrossRef]
53. Baturynska, I.; Semeniuta, O.; Martinsen, K. Optimization of process parameters for powder bed fusion additive manufacturing by combination of machine learning and finite element method: A conceptual framework. *Procedia CIRP* **2018**, *67*, 227–232. [CrossRef]

Article D

JOURNAL OF ENGINEERING DESIGN
https://doi.org/10.1080/09544828.2021.1950656

Taylor & Francis
Taylor & Francis Group

Design for test and qualification through activity-based modelling in product architecture design

Olivia Borgue [a], Christopher Paissoni [b], Massimo Panarotto [a], Ola Isaksson [a], Tommaso Andreussi [c] and Nicole Viola [b]

[a] Industrial and Materials Science, Chalmers University of Technology Göteborg, Gothenburg, Sweden; [b] Mechanics and Aerospace Engineering (DIMEAS), University of Turin and Polytechnic of Turin Centre for Research on Studies in Europe and in the Mediterranean, Turin, Italy; [c] Space Systems, SITAEL SpA, Ospedaletto, Italy

ABSTRACT

Test and qualification (T&Q) phases take a significant portion of the time to market for critical products in the space industry, especially when introducing new technologies. Since T&Q are treated as standard procedures, they tend to be independent of the architectural design phases and kept away from design decisions. However, when introducing new technologies, qualification procedures may differ from those established in regular design scenarios, and the estimation of qualification costs and duration is problematic. There is a lack of design for qualification methods capable of modelling these activities in early phases and use those models to support the architecture design of products with affordable test and qualification phases. In this article, a computer-assisted, model-based design method to model T&Q activities concerning early product architecture designs is proposed. Product architecture alternatives, test schedules and cost are connected through the quantification of T&Q drivers and driver rates. The design method is demonstrated using a case study about electric propulsion for satellites. The method is applicable for design situations where the choice of technology has a strong dependence on the qualification procedure.

ARTICLE HISTORY
Received 10 February 2020
Accepted 29 June 2021

KEYWORDS
Qualification; space industry; model-based design; product architecture

1. Introduction

To remain competitive in the market, companies strive to introduce new technologies to increase product performance and reduce costs and time to market. These technologies often introduce changes in the product's architecture, which is defined as the product's basic physical building blocks and their interactions (Ulrich and Eppinger 2015).

Research has shown that designers are prone to developing product architectures that maximise the implementation and benefits of new technology based on performance, functionality and projected product cost (Wyatt, Eckert, and Clarkson 2009; Borgue, Panarotto, and Isaksson 2019). Consequently, they risk missing to include the impact that the integration of new technologies may bring onto the realisation process (Tatikonda and

CONTACT Olivia Borgue borgue@chalmers.se Industrial and Materials Science, Chalmers University of Technology Göteborg Gothenburg, Sweden

Rosenthal 2000). This tendency is also present in high-cost, high-reliability industries, such as the space industry, where established realisation processes have evolved through deep knowledge of the behaviour of the technologies utilised.

In recent years, there has been an increase in the demand for access to space, with new actors competing for market shares. Market developers now expect leaps in cost decrease and time to market while maintaining high reliability (Öhrwall Rönnbäck and Isaksson 2018). Incentives to introduce novel and high-potential technologies and manufacturing techniques are high.

However, the rigorous processes required to test and qualify new technologies extend the actual lead time for testing procedures, and due to the uncertainty of their outcome, there is a risk of long design iterations (Engel and Barad 2003; Dordlofva et al. 2019). Moreover, as qualification procedures for new technologies can differ from those standardised for regular design scenarios, test phases may further increase costs and redesign iterations (Dordlofva et al. 2019). Therefore, the ability to account for qualification procedures in early design phases has become increasingly important.

The early consideration of qualification requirements, through design for qualification (DfQ) strategies, would support the design of architectures with affordable test and qualification phases and reduce redesign iterations (Wang, Azarian, and Pecht 2008; Dordlofva et al. 2019), reducing the duration and cost of the product development process (PDP) as well. Once the product architecture is successfully implemented, the designer can choose between optimising its performance and reducing the cost of realisation, where test and qualification activities play an important part.

A well-known limitation for early design assessment of test and qualification activities is the lack of model-based methods (methods based on the implementation of models) to estimate the duration and cost of these activities (Tahera et al. 2019). Therefore, this study aims at answering the following research question:

> How can qualification activities be modelled during preliminary design to support design efforts and reduce future redesign iterations?

This article aims to propose a method for modelling test and qualification activities that enables designers to include unique requirements stemming from test and qualification (T&Q) of new technologies when exploring alternative product architectures. A case study from a technology-development project at a satellite space propulsion manufacturer serves to illustrate this method.

2. Background

2.1. Test and qualification activities in the product design and development process

Test activities are performed throughout the PDP to attain different objectives, from concept development to detailed design (Tahera and Earl 2018). Among test activities, qualification activities are performed to demonstrate that a product meets specified safety and legislative norms and quality and reliability requirements (ISO 2020). Similar objectives can be attributed to the verification, validation and testing (VVT) activities in the systems engineering field (Shabi, Reich, and Diamant 2017). VVT activities are performed throughout a PDP before delivering or marketing products for ensuring product quality. Verification is most often used to test the fulfilment of requirements, whereas validation activities test the fulfilment of stakeholders' needs and expectations. The ISO/IEC/IEEE 12207-2:2020(E) standard draws a clear parallel between verification and qualification activities (ISO 2020).

Design development and test activities are performed iteratively throughout the PDP. Data obtained from test activities can be expensive both in terms of cost and time. For this reason, how and when these data are used is critical, as it can impact the cost and duration of the product development activities.

In their review of the modelling of test activities, Tahera et al. (2019) argue that most modelling methods focus on the schedule of a given set of design and test activities to optimise development times. Other studies are concerned with choosing the most appropriate test activities in terms of cost and risk.

Engel and Barad (2003) and Tahera et al. (2019) indicate that the cost of test activities can be as much as 55% of the total life cycle cost. Moreover, test activities depend on product architectures and design contexts; therefore, they should be adapted to different product architecture scenarios (Wang, Azarian, and Pecht 2008).

However, the reviewed literature does not provide mechanisms to enhance the conceptual design phases with insights (or requirements) from the T&Q phases. There seems to be an underlying assumption that there is enough upfront information about the technologies considered, the product itself, as well as how the T&Q of these technologies can be conducted. However, when introducing new technologies, information about product design and the corresponding T&Q activities may not be available. Consequently, test phases can result in unexpected costs or difficulties that lead to expensive redesign iterations (Wang, Azarian, and Pecht 2008; Dordlofva et al. 2019).

2.2. Modelling test activities to support DfQ in early design phases

To model T&Q activities and connect them to product architecture requirements, the factors or variables that influence the cost and duration of these activities must be first identified. In this article, those factors are referred to as T&Q drivers.

The notion of a *driver* is used in literature to describe the causes that affect the output of a system. The term – in this case, *cost driver* – is usually implemented when referring to factors that cause a change in cost (Shank 1989). Authors such as Ben-Arieh and Qian (2003), for instance, developed a parametric cost-estimation model for modelling costs of manufacturing activities using cost drivers of machined parts; the authors identified activity cost drivers (ACD) for the manufacturing processes. For each ACD, they defined activity cost driver rates (ACDR) as the total activity cost divided by the number of cost drivers. Their cost model allows for modelling the costs of manufacturing activities in the early design and development phases.

However, as authors such as Shabi, Reich, and Diamant (2017) and Tahera et al. (2019) point out, the identification of activity drivers and the consequent model of test activities have received significantly less attention in the research community in comparison with other design and analysis activities in a PDP.

Some authors, such as Wyatt, Eckert, and Clarkson (2009) and Tahera et al. (2019), mention that design complexity, product architecture, degree of novelty, the timing of testing and susceptibility to design change affect the duration and cost of test activities. Moreover, when redesigning or upgrading a product, companies attempt to limit the implementation of new components as they increase test activities. These factors are identified as test drivers. These studies, however, do not present a clear statement about the extent to which those drivers affect test activities or how test activities can be modelled and linked to product architecture. Similar insights about VVT activities can be found in literature, for example, in the work by Shabi, Reich, and Diamant (2017). However, the relationship between VVT drivers and product architecture is not established directly.

Dordlofva et al. (2019) presented a compendium of qualification drivers extracted from manufacturers of space components but did not explain further their influence on product architecture design or selection. There is a need for DfQ methods that connect product architecture design phases to T&Q activities; this connection can be achieved by modelling T&Q activities. The main contribution of this article is a model-based design for the qualification method to link T&Q activities to early design phases through the identification of T&Q drivers.

3. Research methodology

A case where qualification has a direct impact on the selection of new technologies and the concept selection for new products was identified within an advanced manufacturing demonstration project for next-generation satellite-propulsion systems. The project is part of Horizon 2020, funded by the European Commission, with the objective of developing three different electric propulsion subsystems.

This article is focused on developing a T&Q model and its implementation during the conceptual design phases of an electric propulsion system (EPS). The study focused on conventional EPS architectures, implementing a power-processing unit (PPU), and innovative EPS architectures, implementing a direct drive (DD) technology (Impresario 2015).

The core of the data collection activities for this study was performed during a three-month visit to a satellite manufacturer participating in the project. During this period, the first and second authors worked on site in collaboration with the EPS design team. Full access to real company data and the possibility to perform interviews and participate in their technical meetings were provided. The second author already worked at the company in a supporting role for mission analysis. The first author had the role of an observer to gather data during the study. The authors invested the equivalent of 60 full working days (8hs/day) in the data collection activities of this study.

The information gathered can be divided into (1) information gathered from documented sources (documented information) and (2) information gathered through interactions with practitioners (tacit information). Information-gathering activities are detailed in Sections 3.1 and 3.2.

From the study, a generic method for modelling T&Q activities and including them in early design phases was developed. The method aimed at supporting architectural design decisions and developing products with affordable T&Q phases. The method was applied for the design of a high-power propulsion system for space exploration.

The performed activities are schematised in Figure 1 and hereby presented.

3.1. Data collection of documented information

The data collection of documented information was performed through the analysis of the company's internal documentation, including mission-specific (where and how the

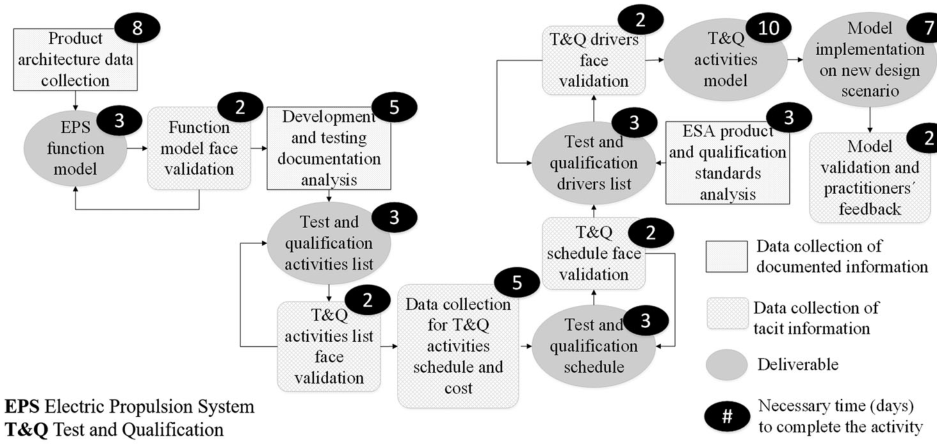


Figure 1. Research methodology diagram illustrating the performed data collection activities and time for activity completion.

product was going to be utilised) and product-specific (design and test requirements to comply with the specific mission) documents. As presented in Figure 1, the first data collected were stored in a function-means model of the EPS (Claesson 2006). A function model was preferred, as it facilitates product architecture understanding and the establishment of system boundaries (Müller, Siiskonen, and Malmqvist 2020), assessing the components, subsystems and interactions that were going to be included in the study.

Later, documentation about product development and testing was gathered and documented in preliminary lists. Those lists and further information collected about activity schedules were later stored in Gantt and PERT (Program evaluation and review technique) charts.

Finally, another portion of the data was obtained from the ESA's product and T&Q standards for space components, such as ECSS-Q-ST-70-45C for mechanical testing of metallic materials (ECSS 2008), or ECSS-Q-ST-60C Rev.2 for electrical, electronic and electromechanical components (ECSS 2013). This documentation supported the identification and analysis of the drivers that motivate the implementation, cost and duration of T&Q activities.

3.2. *Data collection of tacit information*

In addition to the collection of documented information, a series of meetings and semi-structured interviews with company practitioners was performed. As presented in Figure 1, most of the meetings were held to validate 1) the EPS function model, 2) the T&Q list, 3) the T&Q schedule, 4) the T&Q drivers, and 5) the T&Q activities models.

Semi-structured interviews were held to gather information about the best-, average- and worst-case scenario for activity cost and duration. Moreover, the interviewees were requested to provide information about the activities' sequences. Data obtained from different participants and documented information were compared, and when discrepancies were found, additional meetings were held. The meetings and interviews for the data collection of tacit information were held with seven company practitioners, with an average of 10 years of expertise in the areas of systems engineering, design and T&Q of EPS. Each meeting lasted between one and two hours.

During the interviews, practitioners were also asked about the factors that influence the cost (cost drivers) and duration (duration drivers) of T&Q activities. However, the information gathered about cost and duration was further analysed to find commonalities and trends among activities and their relation to architectural components. This analysis was performed to find cost and duration drivers not mentioned by the practitioners.

The performed data collection and study led to the development of the method proposed in this article for modelling T&Q activities and its implementation to support product architecture design decisions. The proposed method is introduced in the following section.

4. Modelling T&Q activities for supporting architecture design decisions

This section presents a DfQ method and its implementation to support product architecture design decisions. The method is based on identifying the factors that drive (drivers) duration and cost of T&Q activities and their interaction with activity schedules.

The input of this method is the current product design information, such as CAD files, datasheets, etc., and the T&Q activities related to it, such as development and testing documentation. The outputs of this method are the total cost and duration of T&Q phases and a T&Q model, which can then be implemented to estimate the duration and cost of the T&Q activities for future product architectures. The T&Q model and the cost and duration of each T&Q activitiey are used to support the design of product architectures with affordable T&Q phases.

To support design decisions, the DfQ method combines function-modelling techniques, which support the decomposition and visualisation of alternative product architectures, with the identification and quantification of T&Q drivers to model T&Q activities.

Figure 2 presents the proposed method, which can be divided into six steps presented in the following sections.

4.1. *Step 1: construct function model*

With information about product architecture and design, a function model of the product is constructed. Function models are representations of the hierarchical decomposition of a product's functional requirements (Claesson 2006). In this article, the function-modelling technique preferred is enhanced function-means (EF-M), which associates one design solution (DS) with each functional requirement (FR) (Claesson 2006; Müller, Siiskonen, and Malmqvist 2020), as presented in Figure 3, left. Interactions between the DSs can be modelled using "interacts with"' connections. Such interactions can be of four types: geometry, signals, energy, and material flow. In this article, DSs are used to represent components or component assemblies.

4.2. *Step 2: construct PERT diagram*

In this step, PERT diagrams are constructed (Dodin 1985). These representations facilitate the understanding of the T&Q workflow and are necessary for performing a calculation of the total duration of T&Q activities.

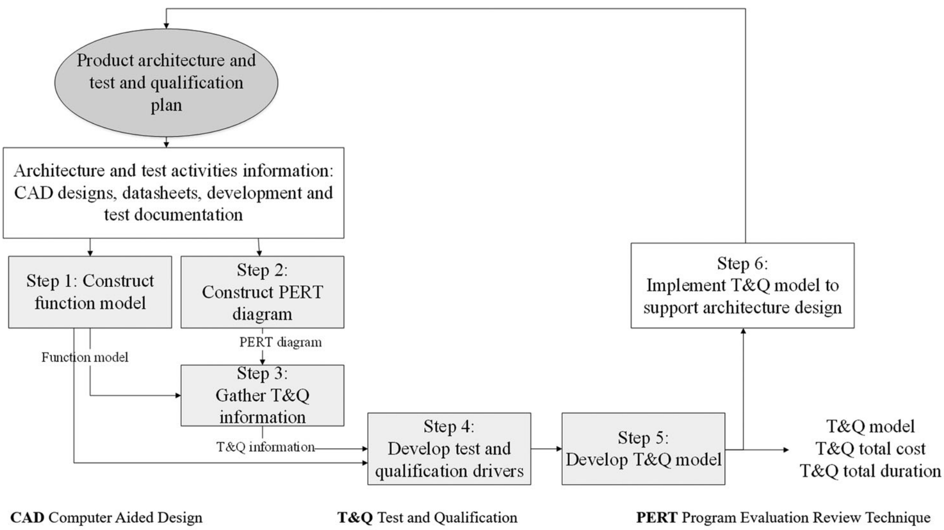


Figure 2. Process diagram of the design for qualification method.

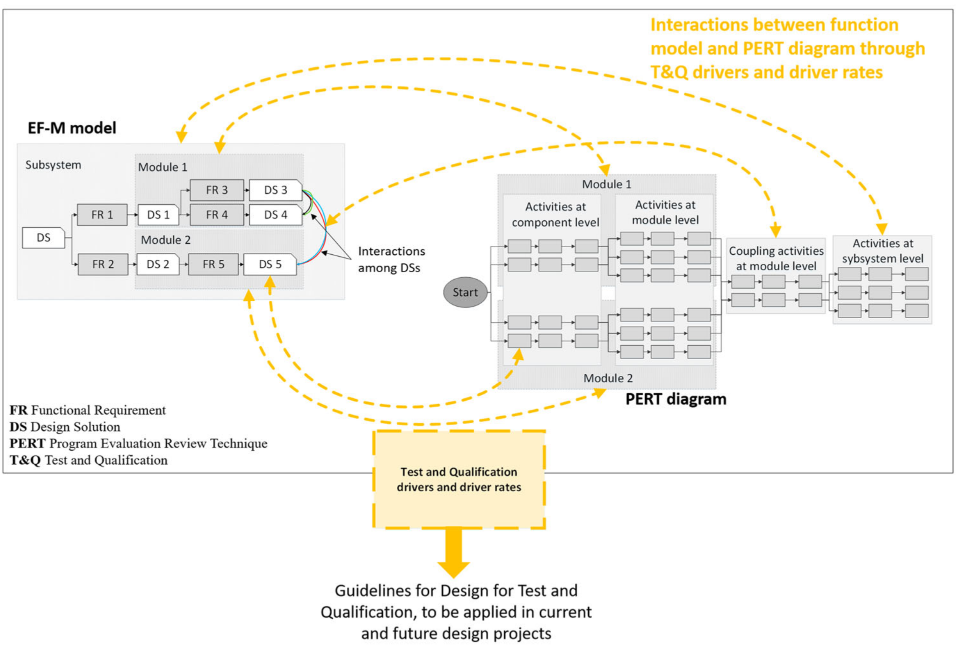


Figure 3. EF-M (Enhanced Function-Means) elements representing a product architecture (left) and activities performed for testing and qualifying such architecture (right). Their connection through test and qualification (T&Q) drivers enables the proposed design for qualification method.

Using the function model as a visual guideline of product architecture, T&Q activities should be grouped according to the system level they belong to (system, subsystem, module or component level). Generally, every activity in the PERT diagram must have a corresponding element in the product architecture; however, several activities can share the same element. The function model, in this case, provides a structure for T&Q activity identification, as it can depict interfaces among components or subsystems, interfaces which are often tested, as highlighted with dashed arrows in Figure 3.

4.3. Step 3: gather T&Q activities' information

Step 3 concerns gathering information about the duration and cost of T&Q activities. The duration and cost of each activity are represented by a beta probability distribution function (PDF). In a beta probability function, the area under the curve on the right side of the most likely activity completion time is greater than the area on the left side, representing the human tendency to extend the duration of a task to fill the available completion time (Browning and Eppinger 2002). In this article, however, the beta representation is estimated by a triangular distribution, using three values for activity duration: best-case, most likely, and worst-case scenario durations. The height of a triangle distribution (the most likely activity duration) is normalised; therefore, the area under the distribution equals one. This estimation has been extensively implemented by authors such as Browning and Eppinger (2002) or Wu (2016).

Step 3 is focused on details for breaking down cost and duration information. For example, if 20 h are required to test electronic equipment, the duration breakdown may include a list of every test performed, their duration and sequence (which, in the end, will add up to 20 h). A cost breakdown would include information about necessary resources for the tests, such as the number of engineers or technicians, equipment implemented and consumables.

The information gathered in this step enables the construction of a Gantt chart of the T&Q activities, which facilitates the assessment of schedule and activity duration by practitioners (Wilson 2003).

4.4. Step 4: develop T&Q drivers

In Step 4, T&Q drivers are identified by analysing the data obtained in the previous steps.

After their identification, activity driver rates for each driver are established. In research conducted by Ben-Arieh and Qian (2003), the authors identified ACDs and their respective ACDRs for manufacturing processes.

For example, the authors determined that the activity "Discuss product (manufacturing)" had a total cost of $17.53. After performing a cost breakdown, it was found that such cost was driven by the "Number of tool changes", which in their case was equal to six (six tool changes were performed). Therefore, the activity cost driver rate for the driver Number of tool changes is $\$17.53 / 6 = \$2.91$.

In Step 4, ACD and ACDR are identified for each T&Q activity. Moreover, following the logic behind the definition of ACD and ACDR, activity duration drivers (ADD) and their respective activity duration driver rates (ADDR) are identified as well. The identification of ADD and ADDR enables the assessment of T&Q activities' duration in early design phases.

4.5. Step 5: develop T&Q model

By implementing the T&Q drivers and their respective driver rates, the duration and cost of such activities can be modelled in relation to the product's architectural features. As

Ben-Arieh and Qian (2003) have previously proposed, the cost of a manufacturing process defined by ACDs and ACDRs can be modelled as $\sum_{i=1} ACD_i x ACDR_i$. The same principle can be implemented to model the duration and cost of T&Q activities once ACDs and ACDRs are identified. Then, implementing the PERT diagram from Step 2, the total cost and duration of the T&Q phase are obtained through an activity network calculation code that reduces the whole activity schedule to one equivalent activity, as proposed by Dodin (1985).

4.6. Step 6: implement T&Q model to support architectural design

The developed T&Q model is implemented to support architectural design and selection in early design phases (bottom of Figure 3).

5. Applying the DfQ method on a high-power EPS design

The proposed DfQ method is illustrated with the analysis of an already developed 5 kW hall thruster (HT) EPS. The analysis performed on this thruster enables the development of T&Q models to support the development of a future high-power (20 kW) HT EPS architecture.

A conventional EPS for an HT comprises a PPU, a fluid management system (FMS) and a thruster unit (TU), which comprises a thruster and a cathode. A conventional EPS architecture is presented in Figure 4. The EPS is fed by the satellite's power-generation system (PGS), consisting of solar arrays (SA), a power bus and batteries. The PPU modulates the power from the power bus, controls the operation of the subsystem components and provides housekeeping telemetries.

Thrust is generated and sustained by the TU and cathode, ionising propellant, typically xenon, provided by the FMS. The ionised propellant (plume) is accelerated with a magnetic field, propelling the satellite (Impresario 2015).

To ensure compliance with quality requirements, different tests are performed at component, module and subsystem levels. Some tests include mechanical tests, such as vibration and shock tests, and vacuum tests, performed in an adequate vacuum environment with high pumping capabilities (ECSS 2018). The long duration and high costs of these tests constrain the product development schedule.

Through each development and test step, different physical thruster models are implemented following the ECSS standards (ECSS 2018). These models include (1) an engineering model (EM), representative in terms of fit, functionality and form, (2) an engineering qualification model (EQM), which fully respects the final product excepts for standard parts, (3) a proto-flight model (PFM), representing the end product during the qualification tests, and (4) a flight model (FM) as the end product before the acceptance phase.

With the development of increasingly powerful HTs, system complexity and mass may increase.

The main drawbacks of EPSs with conventional PPU arrangement are heavyweight and large volume. A solution can be a direct-drive architecture, with power from the SAs directly transferred to the TU, simplifying the PPU with the removal of the power modules for the operations of the TU and cathode (Impresario 2015).

However, when implementing a DD architecture, the power bus must be designed to sustain the high-voltage levels of the TU. Moreover, the rest of the components of the PGS

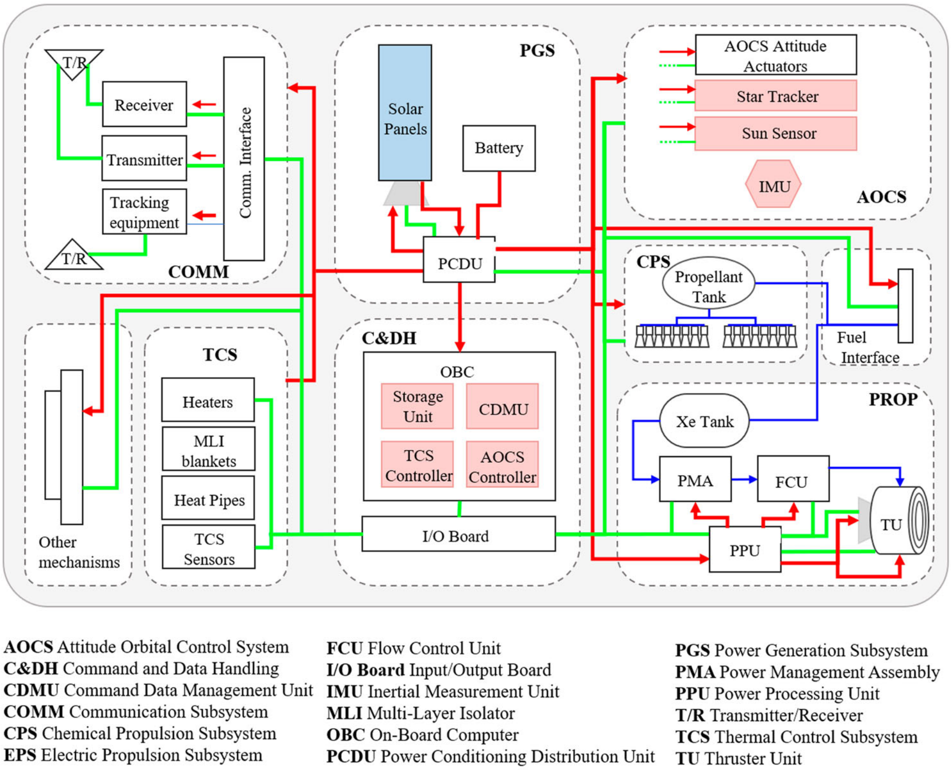


Figure 4. Satellite system architecture.

shall be adapted to cope with high-voltage levels, relaying (in some architectural solutions) on high-voltage SAs. However, an inconvenience of such SAs is the risk associated with arcing and the interaction of the SA with the TU plume. These events require additional T&Q activities (Impresario 2015).

To assess the duration and cost of T&Q activities for a 20 kW HT and implement these insights for making architectural design decisions, a T&Q model for known HT architectures is developed in section 5.1, following the method introduced in section 4. In section 5.2, the model is implemented to support the conceptual design of a 20 kW HT.

5.1. Development of a T&Q model for a 5 kW HT

Following step 1, CAD designs, datasheets and other product architecture data were used to build a function model of the 5 kW HT. Figure 5 illustrates a simplified version of such a model. The model alternates functions with DSs and represents interfaces among components and modules (coloured lines). The work done by Claesson (2006) offers a detailed explanation of the theory and methods for building an EF-M.

From the information gathered about T&Q activities, the PERT diagram presented in Figure 6 was built. In this case, the PPU, the FMS and the TU are different modules of the EPS. Therefore, the EPS and the PGS are subsystems of the satellite system.

In general, the process of building the PERT and function models is iterative. A common complaint about EF-M modelling is the lack of modelling guidelines on what to

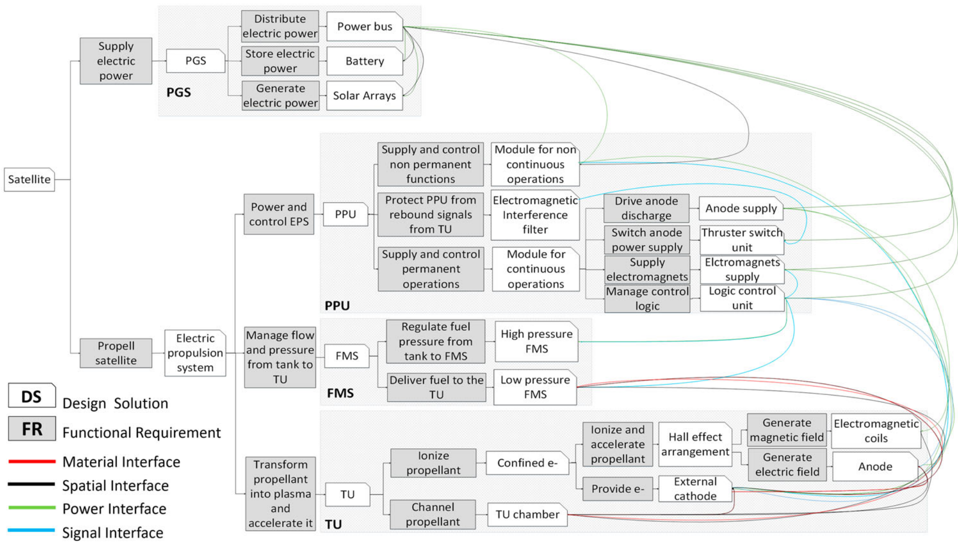


Figure 5. Simplified function model of a hall thruster.

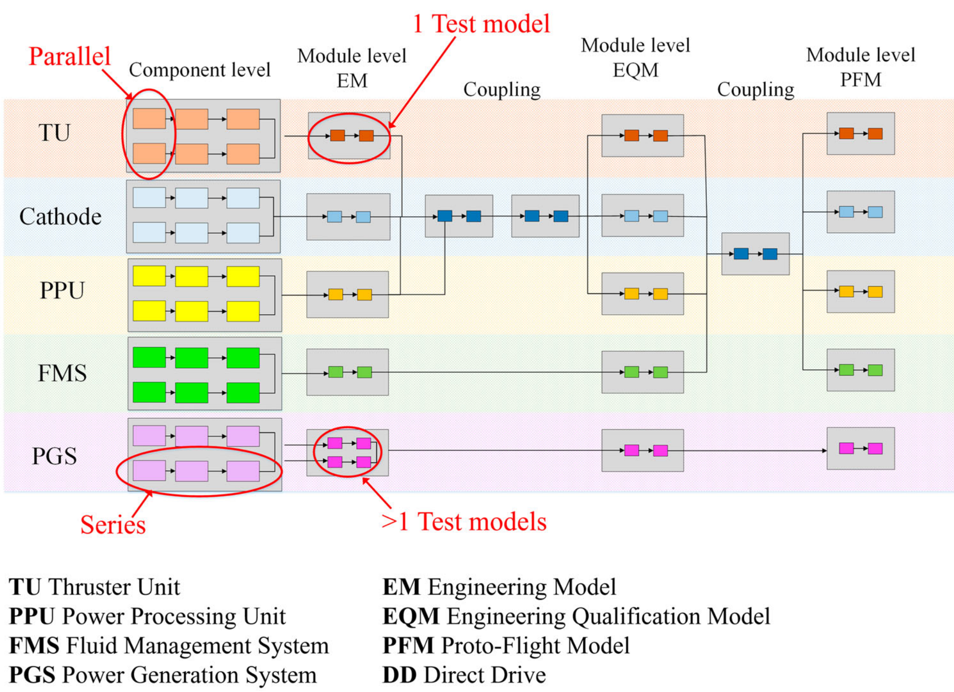


Figure 6. PERT diagram with a simplified representation of the test and qualification activities. Different EPS modules and the PGS are identified with different colours: orange (TU), blue (Cathode), yellow (PPU), green (FMS) and pink (PGS).

include in the model and how (Müller, Siiskonen, and Malmqvist 2020). As every activity in the PERT diagram must have a corresponding element in the product architecture, iterating between the PERT and function models helps in building a complete function model without unnecessary details. Moreover, information from CAD designs and datasheets can evidence elements in the function model without a corresponding test activity. In this case, further efforts to find information about those test activities and include them in the PERT diagram should be made.

In the PERT diagram, testing activities related to single components from the different product modules (such as PPU, FMS, TU and cathode) are performed in series with other activities from the same module but in parallel to activities performed on the other modules. Later, the at module level and EPS subsystem level, testing activities can be performed either in series or in parallel. The choice depends on the implementation of one or more test models (EM, EQM and PFM), as the latter option allows for several activities to be performed in parallel. Figure 6 includes the PGS as well. The PGS is presented in a general way, not distinguishing its modules and components to reduce figure complexity, presenting, however, the T&Q activities performed to evaluate its interaction with the EPS.

Table 1 presents a compendium of the duration and cost of T&Q activities performed at the component level. The details of those activities are not included in the table to preserve company-sensitive information.

Table 2 presents a simplification of the activities performed on different test models (EM, EQM or PFM) for the different EPS modules and PGSs. Only representative activity placeholders were included; this simplification preserves company-sensitive information while supporting the presentation of the proposed T&Q activities model. For the same reason, activity durations and cost values are not representative of the real company data.

From Tables 1 and 2, T&Q duration and cost drivers can be extracted. However, some of the drivers do not depend on the EPS design. This is the case for the duration of the module level tests, which are determined by the satellite mission and standardised test configurations, such as the ECSS-Q-ST-70-45C for mechanical testing of metallic materials (ECSS 2008), or the ECSS-Q-ST-60C Rev.2 for electrical, electronic and electromechanical components (ECSS 2013).

Similar to the procedure followed by Ben-Arieh and Qian (2003) and introduced in Section 4.4, design-dependent driver rates were obtained from the activities in Tables 1 and 2. Some of the driver rates are presented in Tables 3 and 4.

Table 1. Data collected for components in the PPU, FMS and TU modules.

	Duration (days)			Cost (euros)				
Component	B	M	W	B	M	W	Cost remarks	Duration remarks
PPU								
Components without firmware	12	22	35	264	484	770	1 engineer. Proportional to time	Firmware increases duration.
Components with firmware	18	30	45	396	660	990		
FMS								
Mechanic components	6	11	17	110	220	330	New materials, coatings, manufacturing techniques or design geometries increase duration	
Electronic components	12	22	35	264	484	770		
TU								
Electromagnets comp.	6	11	17	110	220	330	Proportional to testing time. Average of 1.5 engineers.	
Anode	10	14	18	220	308	396		
Electromagnet assembly	1	2	4	22	44	88		
PGM								
Electrical components	12	22	35	264	848	770	Proportional to time. 1 engineer	Depends on SA voltage.

Table 2. Data collected for module level.

Cathode	Duration (days) B	M	W	Cost (x10^2 €) B	M	W	Cost remarks	Duration remarks
Tests at EM level	200	340	520	18000	30000	46000	2 engineers. Depends on type of propellant and thruster power. Proportional to time.	Depends on test configuration and satellite mission.
Tests at EQM level	200	340	520	19000	31000	47000		
FMS								
Tests at EM level	16	24	40	180	185	195		
Tests at EQM level	40	70	100	250	255	265		
Tests at PFM level	16	24	40	740	750	770		
TU								
Tests at EM level	140	300	40	4600	5100	5400	2 engineers. Depends on type of propellant, vacuum chamber and number of models tested. Thruster power increases costs. Proportional to time.	
Tests at EQM level	70	100	140	5100	7300	10000		
Tests at PFM level	60	90	120	4400	6600	8800		
PPU								
Tests at EM level	140	300	400	650	690	710	1 engineer. Proportional to time	
Tests at EQM level	70	100	140	2000	21000	23000		
Tests at PFM level	60	90	120	2000	21000	23000		
Other								
Coupling tests	40	60	120	10	14	30	2 engineers	
PGS								
Tests at EM level	140	300	400	900	1200	1500	2 engineers. Proportional to time.	Duration of the electro discharge test depend on voltage level.
Tests at EQM level	70	100	140	2000	2100	2200		
Tests at PFM level	60	90	120	3800	3900	4000		

For example, Table 1 indicates that T&Q activities for PPU components without firmware have a duration of (12, 22, 35) days, and components with firmware have a duration of (18, 30, 45) days. Every PPU component requires at least (12, 22, 35) T&Q days; hence, the number of PPU components (Nmp) is a qualification driver and (12, 22, 35) days/Nmp is its driver rate. PPU components with firmware (Nmf) require (6, 8, 10) extra T&Q days; hence, Nmf is a qualification driver with the driver rate of (6, 8, 10) days/Nmf.

Activity cost drivers that depend on activity duration drivers are not included in Table 4. For example, the number of PPU modules increases the duration of test activities, thereby increasing costs due to an increase in required manpower. However, the number of PPU modules is not considered a cost driver.

In Table 2, the cost and duration of the test activities on the module level depend on the number of models (EM, EQM or PFM) tested. If the number of models tested increases, cost increases as more test models are manufactured; however, the total duration of T&Q activities performed in a module is reduced, as several tests can be performed in parallel. In Table 3, the number of modules tested (Nemd, Nqmd and Npmd) can vary from one to the total number of T&Q activities performed. If the number of PPU EMs is one (Nem $= 1$), every test activity at the PPU EM level is performed in series. However, if the number of PPU EMs is equal to the number of test activities, every activity is performed in parallel.

From the data collected in previous steps, a T&Q dependency structure matrix (DSM) was built (Maheswari and Varghese 2005), as presented in Figure 7, top.

In the matrix, columns and rows represent test activities. Nondiagonal matrix components indicate that an activity in a certain row is dependent on the results from a previous

Table 3. Driver rates for activity duration drivers. Duration is presented in days.

Activity duration drivers					
			Driver rate (days / N of driver)		
Activity		Driver	B	M	W
PPU components test	Nmp	Number of components	12	22	35
	Nmf	Number of components with firmware	6	8	10
PGS components test	Nbu	Number of buses tested	12	22	35
	Nb	Number of batteries tested	12	22	35
	Ncon	Number of converters tested	12	22	35
	Vsa	SA voltage	(Vsa/100)B	(Vsa/100)M	(Vsa/100)W
	Nsa	Number of components on the SA	12	22	35
TU components tests	Nn#	Materials, coating, manufacturing technique or design geometry not implemented in previous projects	*B/(2Nn)	*M/(2Nn)	*W/(2Nn)
	Nc	Number of coils tested	0.5	1	2
	Ne	Number of electromagnets assemblies tested	1	2	4
	Nfe	Number of ferromagnetic parts tested	5	10	15
	Na	Number of anodes tested	10	14	18
FMS	Nfmc	Number of mechanical components	6	11	17
	Nfec	Number of electronic components	12	22	35
Tests at component level	Neg	Number of engineers	(1 < Neg < Number of tests)		
Coupling tests	Nct	Number of coupling tests	40	60	120
All tests on module level	Nem	Number of EM tested	1 < N#m < Number of tests		
	Nqm	Number of EQM tested			
	Npm	Number of PFM tested			

*The driver rate equals a proportion of the test activity. For example, if the anode is manufactured with new manufacturing technologies (such as additive manufacturing), test activities are increased in a 50%.
#Nn# can represent Nnc (coils), Nne (electromagnet), Nnfe (ferromagnetic) and Nna (anode).

activity (or activities). If activity A depends on the results of activity B, A and B are in series, and their durations are added to compute the total T&Q duration. If activities A and B depend on the results of the same activity and their results are necessary for the execution of another activity, A and B are in parallel (Dodin 1985). In this case, only the duration of the longest activity is added to the total. In this way, the DSM is simplified until an equivalent single activity is reached (Figure 7, bottom). When the DSM becomes irreducible, duplication techniques are implemented, as suggested by Dodin (1985).

The DSM presents information in the same way a PERT diagram does; however, it has a better performance in schedule optimisation since it can allow operations such as sequencing or partitioning and tearing (Maheswari and Varghese 2005).

In the DSM, it is assumed that the test activities performed at the PPU component level are performed in series; however, they are performed in parallel to the tests performed at the TU component level. In the same way, only one model (one EM, one EQM and one PFM) is used at the module level. For instance, tests at the PPU module level are performed in series; however, they are performed in parallel to the tests performed at the TU module level.

The main contribution of this article is not the development of an algorithm for activity network calculation. Consequently, to simplify the duration and cost calculations, the activity model assumes that (1) activity durations are independent of each other: Dependencies are only accounted for in the interactions between the activities, and (2) activity duration accounts for any internal rework efforts.

Table 4. Driver rates for activity cost drivers. Duration is presented in days.

	Activity cost driver		
Activity		Driver	Driver rate (euros / N of driver)
All activities	Neg	Number of engineers	22 per hs (Worldsalaries 2019)
PPU	Npeb	Number of EM	50 K(1 + 0.1(Power-5 kW))
	Npeq	Number of EQM	250 K(1 + 0.1(Power-5 kW))
	Npp	Number of PFM	250 K(1 + 0.1(Power-5 kW))
Cathode	Ncem	Number of EM	10 K(1 + 0.1(Power-5 kW))
	Nceq	Number of EQM	20 K(1 + 0.1(Power-5 kW))
	Ncp	Number of FPM	20 K(1 + 0.1(Power-5 kW))
	Tp	Thruster power	**(22Duration)76 × 10^{-5}
FMS	Nfem	Number of EM	75 K(1 + 0.1(Power-5 kW))
	Nfeq	Number of EQM	300 K(1 + 0.1(Power-5 kW))
	Nfp	Number of FPM	300 K(1 + 0.1(Power-5 kW))
TU	Ntem	Number of EM	40 K(1 + 0.1(Power-5 kW))
	Nteq	Number of EQM	80 K(1 + 0.1(Power-5 kW))
	Ntp	Number of FPM	80 K(1 + 0.1(Power-5 kW))
	Tp	Thruster power	**(220Duration) 76 × 10-5
PGS	Ngem	Number of EM	10 K(1 + 0.1(Power-5 kW))
	Ngeq	Number of EQM	30 K(1 + 0.1(Power-5 kW))
	Ngp	Number of FPM	30 K(1 + 0.1(Power-5 kW))

**For Xenon, 760 euros/kg.

Consequently, the most probable total duration and cost of the T&Q activities for the 5 kW EPS are 1,340 days and €64,000,000. These results resonated well with company practitioners.

Modelling T&Q activities

Based on the work presented by Ben-Arieh and Qian (2003), the duration and cost of the T&Q activities can be estimated using drivers and driver rates as

$$Activity\ duration = \sum_{i=1} ADD_i x ADDR_i \tag{1}$$

$$Activity\ cost = \sum_{i=1} ACD_i x ACDR_i \tag{2}$$

In these equations, activity duration and cost are represented by a vector of three components, namely, best-case-, most-probable-case- and worst-case-scenario duration and cost. The analysis was performed assuming that one test model (one EM, one EQM and one PFM) is used. (Tests are performed in series).

For example, the modelling equations for the total duration (equation 3) and cost (equation 4) for activities at a PPU component level are presented below. The rest of the modelling equations can be obtained through equations 1 and 2, after implementing the drivers and driver rates from Tables 3 and 4.

$$DPPU_{comp} = N_{mp}(12,\ 22,\ 35) + N_{mf}(6,\ 8,\ 10) \tag{3}$$

$$CPPU_{comp} = N_{eg} \times 22 \times DPPU_{comp} \tag{4}$$

Where T&Q activity durations:

- N_{mp}: (ADD) Number of PPU components
- N_{mf}: (ADD) Number of components with firmware

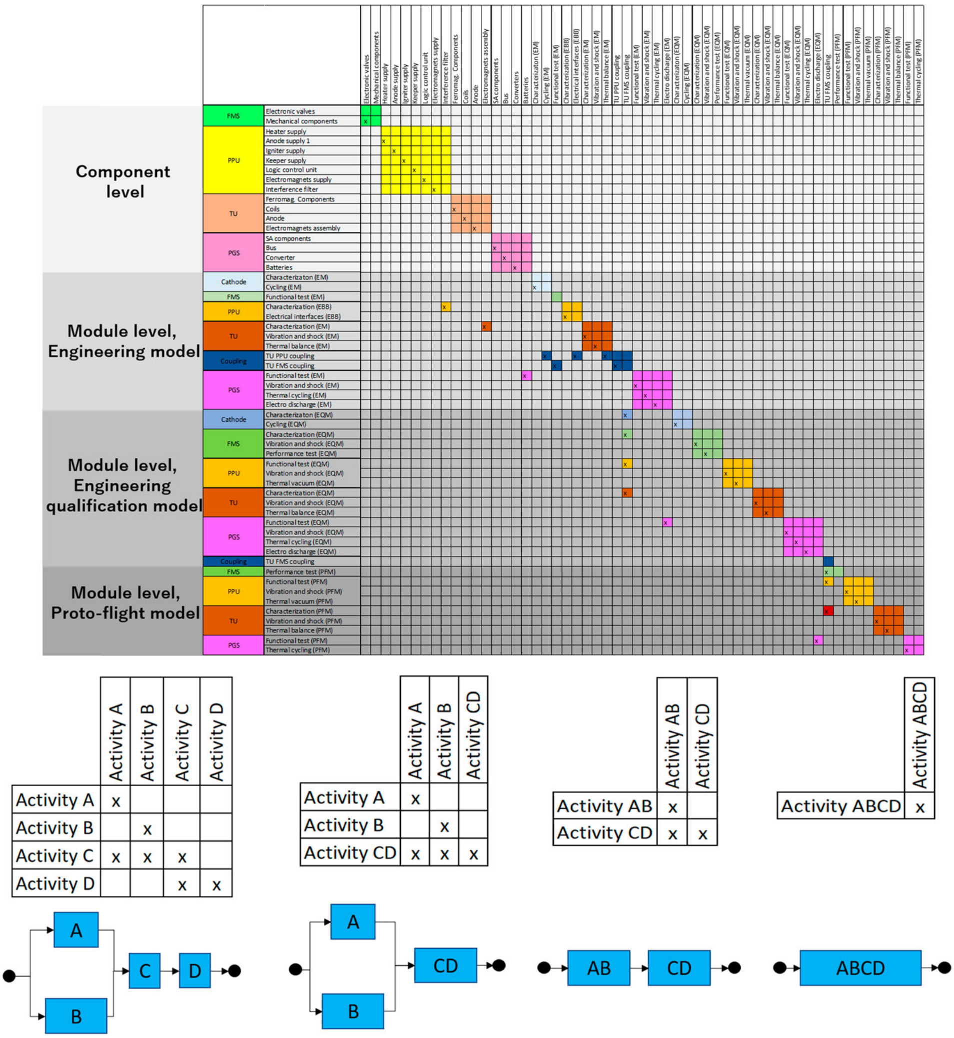


Figure 7. T&Q DSM (top) and operations performed to calculate the total duration of the T&Q phase (bottom). Different EPS modules and the PGS are identified with different colours: orange (TU), blue (Cathode), yellow (PPU), green (FMS) and pink (PGS).

– (12,22,35): Best-case-, most-probable-case- and worst-case-scenario ADDR for Nmp
– (6,8,10): Best-case-, most-probable-case and worst-case-scenario ADDR for Nmf
– T&Q activities cost:
– N_{eg}: (ACD) Number of engineers
– 22 (euros/hrs): engineer's salary (Worldsalaries 2019)

5.2. Application of the T&Q model for architectural design of a 20 kW HT

In this section, the developed T&Q model is implemented to analyse the impact of different product architectures on the duration and cost of T&Q activities and support the development of additional architectures. Five different architectures of a 20 kW HT are analysed. The

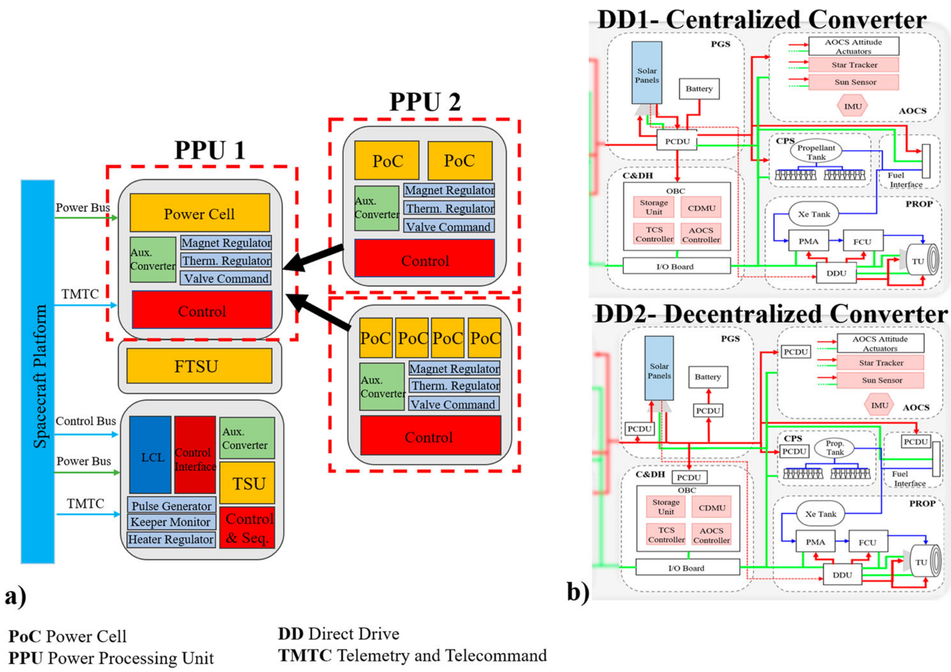


Figure 8. a) PPU architecture alternatives, b) DD architecture alternatives.

first three architectures are based on variations of a conventional PPU module, as presented in Figure 8a. One of the alternatives is a PPU with one 20 kW power cell (PPU1), another with two 10 kW power cells (PPU2) and a third with five 4 kW power cells (PPU3). The advantage of multiple power cells is the possibility to modularise the PPU to make the design flexible and adaptable to future mission requirements.

The last two alternatives are variations of a DD configuration, where the anode module of the PPU is removed and the TU is directly fed from the power bus connected to the PGS. This configuration has the objective of reducing weight, volume and the number of components (Impresario 2015). The TU is directly connected to an HV power bus connected to a high-voltage SA. As other satellite subsystems might require a low voltage, converters are implemented in the PGS to adapt to the power requirements of the different satellite subsystems. One of the DD alternatives, presented in Figure 8b, has a centralised voltage converter (DD1). The other alternative (DD2) has a distributed converter arrangement, where different converters are assigned to different components.

A centralised converter reduces the number of components and the weight and volume of the equipment that protects the converter from radiation degradation; however, it concentrates thermal control efforts to a single hot spot.

The distributed converter arrangement implements a larger number of smaller converters, facilitating modularity, redundancy and design adaptability. However, these smaller converters can increase volume and weight.

Direct coupling between the PGS and the TU implies the implementation of a high-voltage power bus, which leads to the implementation of a high-voltage battery and solar arrays (Hoskins et al. 2003).

One of the concerns that industrial practitioners raised about the DD configuration is that the new interface presumably requires a new coupling test between the TU and the PGS. This new coupling test is modelled as presented in equations 5 and 6.

Duration:

$$DCoupling_{PGS-TU} = (40,\ 60,\ 120)\frac{V_{SA}}{100} \tag{5}$$

$$Cost : CCoupling_{PGS-TU} = N_{eg} \times 22 \times DCoupling_{PGS-TU} \tag{6}$$

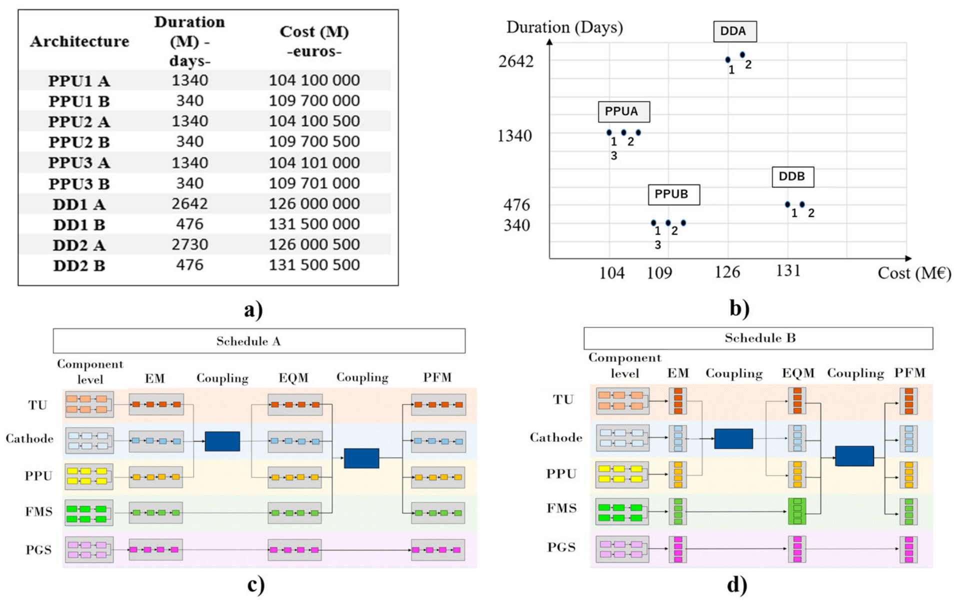
By implementing the T&Q model adapted to the 20 kW HT and equations 5 and 6, the cost and duration of T&Q phases for the five architecture alternatives can be analysed.

Figure 9a (table) and 9b (graph) present the results of the T&Q activities for the five different architectures (PPU1, PPU2, PPU3, DD1 and DD2) performed under two different schedules (Figure 9c–d).

Firstly, a schedule with single test models (only one EM, EQM and PFM for each module) was implemented, denoted with the index "A", as in PPUA or DDA (Figure 9c). This schedule alternative eliminates the possibility of parallel activities inside the modules.

Secondly, a schedule with as many test models as necessary for performing activities on the different modules in parallel was considered, denoted with the index "B", as is PPUB or DDB (Figure 9d).

The three PPUA alternatives (PPU1A, PPU2A and PPU3A) have the same total T&Q duration (1,340 days). This result suggests that the tests performed at a component level in the



Architecture	Duration (M) -days-	Cost (M) -euros-
PPU1 A	1340	104 100 000
PPU1 B	340	109 700 000
PPU2 A	1340	104 100 500
PPU2 B	340	109 700 500
PPU3 A	1340	104 101 000
PPU3 B	340	109 701 000
DD1 A	2642	126 000 000
DD1 B	476	131 500 000
DD2 A	2730	126 000 500
DD2 B	476	131 500 500

TU Thruster Unit
PPU Power Processing Unit
FMS Fluid Management System
PGS Power Generation System
EM Engineering Model
EQM Engineering Qualification Model
PFM Proto-Flight Model
DD Direct Drive

Figure 9. Duration vs. cost distribution of T&Q activities for 10 architecture alternatives (a, b) under two different schedules (c, d).

PPU are not part of the critical path of schedule A. Therefore, an increase in the number of PPU components did not increase the total duration of the T&Q activities; however, their cost slightly increased. The same can be observed with PPUB alternatives. From Figure 9a, the schedule B reduced the total duration of the activities to 340 days, increasing their costs by approximately 5%.

The DDA alternatives have a total duration of 2,642 days (DD1) and 2,730 days (DD2) with costs that are approximately 20% higher than the conventional PPU architecture. This result suggests that the converters are part of the critical path of schedule A.

After implementing schedule B, costs increased by approximately 4%. DDB architectures have T&Q activities with a total duration of 476 days, implying that the T&Q activities for the converters are not in the critical path of schedule B.

These results suggest that architectural changes can have a different, sometimes unintuitive, impact on the T&Q activities, depending on the part of the system they are implemented in.

Moreover, the duration of the T&Q activities for conventional PPU configurations for 20 kW HT and 5 kW HT is the same, as the identified drivers for activity duration are independent of the thruster power. However, the T&Q of a 20 kW HT is estimated to be 60% more expensive than the T&Q of a 5 kW TH. These results resonated well with estimations made by company experts.

DD architectures enable a reduction in weight and volume (Hoskins et al. 2003), corresponding to a reduction in the number of components (the anode supply is removed from the PPU) and component interfaces (the two interfaces, PGS-anode supply and anode supply-anode, are replaced with the interface PGS-TU), as presented in Figure 10.

In Figure 10, the cost and duration of T&Q activities for PP1A and DD1A are compared. The activity DSMs have been colour-coded from green (low cost/duration) to red (high cost/duration).

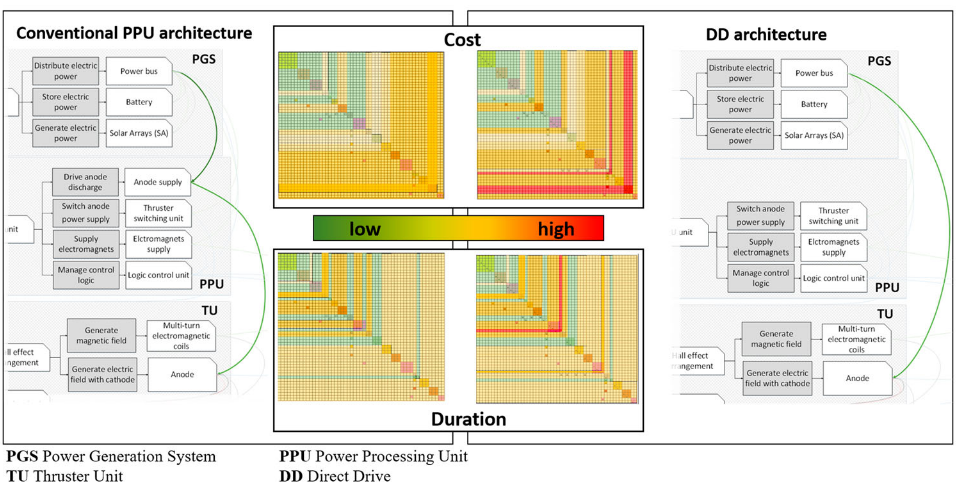


Figure 10. Comparison of PPU and DD architectures. In the middle, DSMs have been colour-coded to compare activity cost and duration for both architecture alternatives.

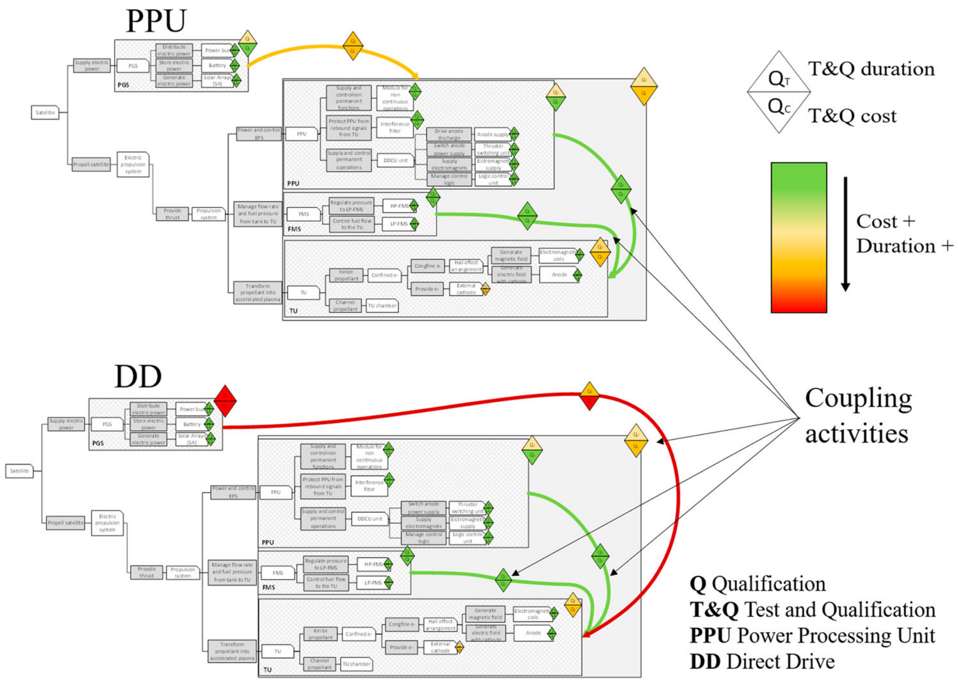


Figure 11. Representation of T&Q duration and cost in a function model scheme.

However, this component reduction negatively impacts the duration and cost of the T&Q performed and visualised in the colour-coded DSMs in Figure 10 as the red rows and columns. This increase is mostly related to the high-voltage components and the coupling tests between the TU and the SA.

In Figure 11, the colour-coded DSMs are represented in a function model scheme to visualise the T&Q duration and cost of different architectural components. In this figure, the activities in the DSM are connected to their corresponding design solutions (white boxes) in the function model, as diamonds. These diamonds indicate activity duration (top) and cost (bottom) and are colour-coded from green to red, as done in Figure 10.

The model implementation and visualisation of its results in Figure 11 suggest that to render the DD architectures conveniently, test activities related to the SA and coupling between the TU and the SA must be redesigned. Moreover, design efforts should focus on redesigning the components or interfaces that undergo long and expensive tests. One solution can be the implementation of dedicated SAs (physically separated SAs with different voltages), reducing the number of converters and the consequences of the interaction between the SA and the TU plume (Impresario 2015).

6. Discussion

The proposed DfQ method supports the development of products with affordable T&Q phases. The method is based on modelling T&Q activities by linking product architecture and test schedule through the identification and quantification of drivers and driver rates, as proposed by Ben-Arieh and Qian (2003). In this article, their work is taken one step further to support architectural design trade-off decisions to reduce the duration and cost of the PDP while still developing a reliable product.

The DfQ method is not intended to frame T&Q requirements as the only requirements to be addressed during architectural design. The method and proposed models are tools for facilitating the introduction of T&Q requirements in early multidisciplinary design trade-offs.

Identifying and quantifying drivers and driver rates allow the identification of test-intensive components, modules and subsystems. Table 1 evidences that electrical components undergo longer testing and incur more costs than mechanical TU components. Moreover, it is possible to identify the longest and more expensive tests (Figures 10 and 11).

In the case study, significant differences were observed between the duration and cost of T&Q activities for architectures with conventional PPU and architectures with DD. The results suggest that conventional PPU architectures can be modularised and designed to be adaptable to different requirements of an EPS product family without incurring higher costs and longer T&Q phases. In the case of the DD configuration, however, adaptability and modularisation are penalised with longer and more expensive T&Q phases.

In this context, by implementing the DfQ method, the expensive and long T&Q activities for a DD architecture can be identified and targeted for redesign. In the same way, the DD components and interfaces that undergo long and expensive tests can be also identified and redesigned.

The DD configuration changes not only the PPU architecture at a component level but also the subsystems interfaces. These modifications at the subsystem interface level lead to additional test activities and modifications at the component level in the PGS. The impact that design changes have on T&Q duration and cost depends on the system level affected. Therefore, the importance of computer-based schedule calculations is based on the DSMs.

In this context, the presented method can facilitate communication and cooperation between the development and testing departments, where colour-coded activity DSMs from Figure 10 and the function model from Figure 11 can function as boundary objects. The method, therefore, enables the concurrent design of product architecture, T&Q schedule and T&Q activities as well. This fact is particularly interesting for the implementation of new technologies or in any other design situation where the qualification phases might not be well defined.

The data gathering and model development for this method was performed for the equivalent of 60 working days (8hs/day; Figure 1), in the context of a product with qualification phases lasting around 1,400 days (4%). However, these activities included the development of the method, where the information and models are meant to be updated with each development project of similar nature in a design organisation.

The time to perform the study is likely to depend on the type of product to be designed, the components and the design context, which is why the effort needed to perform it cannot be generalised.

To increase the capabilities of the method and the accuracy of its results, three areas of improvements have been identified:

- In this study, the activity model and, consequently, the DSM have been simplified assuming that activity durations are independent of each other and that activity duration accounts for rework efforts. However, the DSM representation was preferred, as it enables future calculations about the interdependencies and overlapping of activities, the design iteration and the schedule optimisation, as proposed by Maheswari and Varghese (2005) or Huang and Chen (2006). These capabilities can improve T&Q estimations and contribute to cost and duration optimisation.

- Companies designing products for space applications strive for extreme reductions in cost and time to market while maintaining high reliability. Relaxing qualification requirements of individual units is an increasingly popular alternative among, for instance, mega satellite constellation developers to reduce costs and time to market (Öhrwall Rönnbäck and Isaksson 2018). In this case, reliability is achieved at the mega-constellation level instead of the unit level (Sánchez, Soares, and Wolahan 2017). Regardless of the preferred approach to attain reliability, T&Q models can be combined with risk analysis strategies to assess the risks (product and financial) of not performing (or partially performing) certain T&Q activities. In this case, the risk would be considered a T&Q driver. An example of risk assessment in the context of VVT activities can be found in the work of Engel and Barad (2003). Efforts to include risk assessments in the proposed methodology are currently ongoing. These efforts propose the implementation of fuzzy logic techniques for modelling technology uncertainties and risks related to T&Q in space products.
- Cost and duration were modelled with a triangular PDF as a simplification of beta PDFs. This modelling choice assumes that the shape of PDFs is known and able to be represented as beta functions (Liberatore 2002). To improve the representation of duration and cost probability, a fuzzy logic modelling strategy can be adequate, as previously demonstrated by Liberatore (2002) or Masmoudi and Haït (2012).

The presented model-based DfQ method is meant to be generalised for the integration of new technologies into product architectures. The case study in this article is specific to the EPS design of a satellite thruster. As such, generalised validity will require the method to be repeated on other technologies and other product contexts.

An appropriate method validation must be based on validation strategies for design methods, such as the one proposed by Pedersen et al. (2000). Emphasis should be on evaluating whether the results obtained (products with affordable T&Q phases) are related to the method application and not to other factors. Such a study can compare design outputs from different design teams, some with the DfQ method and some without.

Conclusion

In this article, a model-based DfQ method for integrating T&Q procedures into the conceptual design and evaluation of product architectures is presented. The novelty of the method lies in linking product architecture alternatives with T&Q activities and schedules through the identification and quantification of T&Q drivers and driver rates. It is demonstrated how the method implemented in the case of a satellite thruster component allows designers to design their components to mitigate the substantial risk of design iterations due to late discovery of qualification issues.

It is proposed that by defining qualification drivers, the defining characteristics of a qualification procedure can be quantitatively modelled and integrated into a design study where alternative technologies and concepts are investigated. Therefore, the method can be applied to various design situations where the choice of technology has a strong dependence on the qualification procedure. However, further validation of the method's generalisability is required and is left for future research activities in this domain.

The DfQ method was utilised to model T&Q phases for a 5 kW hall thruster. After implementing the T&Q model, qualification procedures were integrated into the conceptual design and evaluation process of a 20 kW thruster.

Acknowledgements

This study is based on the results from project CHEOPS (Consortium for Hall Effect Orbital Propulsion System), which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730135.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by European Union's Horizon 2020 research and innovation programme [Grant Number 730135].

ORCID

Olivia Borgue http://orcid.org/0000-0001-8886-2323
Ola Isaksson http://orcid.org/0000-0003-0373-3720

References

Ben-Arieh, D., and L. Qian. 2003. "Activity-based Cost Management for Design and Development Stage." *International Journal of Production Economics* 83 (2): 169–183.

Borgue, O., M. Panarotto, and O. Isaksson. 2019. "Modular Product Design for Additive Manufacturing of Satellite Components: Maximizing Product Value Using Genetic Algorithms." *Concurrent Engineering* 27 (4): 331–346.

Browning, T. R., and S. D. Eppinger. 2002. "Modeling Impacts of Process Architecture on Cost and Schedule Risk in Product Development." *IEEE Transactions on Engineering Management* 49 (4): 428–442.

Claesson, A. 2006. "A Configurable Component Framework Supporting Platform-Based Product Development." PhD thesis, Chalmers University of Technology, Gothenburg, Sweden.

Dodin, B. 1985. "Bounding the Project Completion Time Distribution in PERT Networks." *Operations Research* 33 (4): 862–881.

Dordlofva, C., O. Borgue, M. Panarotto, and O. Isaksson. 2019. "Drivers and Guidelines in Design for Qualification Using Additive Manufacturing in Space Applications." In *Proceedings of the Design Society: International Conference on Engineering Design*, edited by S. Wartzack, B. Schleich, and Gon, 729–738. Cambridge: Cambridge University Press.

ECSS. 2008. "ECSS-Q-ST-70-45C – Mechanical Testing of Metallic Materials." ECSS-European Cooperation for Space Standardization. https://ecss.nl/standard/ecss-q-st-70-45c-mechanical-testing-of-metallic-materials/.

ECSS. 2013. "ECSS-Q-ST-60C Rev.2 – Electrical, Electronic and Electromechanical (EEE) Components." ECSS-European Cooperation for Space Standardization. https://ecss.nl/standard/ecss-q-st-60c-rev-2-electrical-electronic-and-electromechanical-eee-components-21-october-2013/.

ECSS. 2018. "ECSS-E-ST-10-02C Rev.1 – Space Engineering - Varification." ECSS-European Cooperation for Space Standardization. https://ecss.nl/standard/ecss-e-st-10-02c-rev-1-verification-1-february-2018/.

Engel, A., and M. Barad. 2003. "A Methodology for Modeling VVT Risks and Costs." *Systems Engineering* 6 (3): 135–151.

Hoskins, A., D. Homiak, R. J. Cassady, T. Kerslake, T. Peterson, D. Ferguson, D. Snyder, I. Mikellides, G. Jongeward, and T. Schneider. 2003. "Direct drive Hall thruster system development." 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit.

Huang, E., and S. J. Chen. 2006. "Estimation of Project Completion Time and Factors Analysis for Concurrent Engineering Project Management: A Simulation Approach." *Concurrent Engineering* 14 (4): 329–341. doi:10.1177/1063293X06072482.

Impresario, G. 2015. "Design and simulation of a 5 kW Hall Thruster direct drive experiment." Corso di Laurea Specialistica in Ingegneria Aerospaziale, Tesi di Laurea, Dipartimento di Ingegneria Civile e Industriale, Università di Pisa.

ISO/IEC/IEEE. 2020. ISO/IEC/IEEE 12207-2:2020(E), Systems and Software Engineering — Software Life Cycle Processes, Part 2: Relation and Mapping Between ISO/ IEC/IEEE 12207:2017 and ISO/IEC 12207:2008, 4–27. Vernier, Geneva: ISO/IEC/IEEE.

Liberatore, M. J. 2002. "Project Schedule Uncertainty Analysis Using Fuzzy Logic." *Project Management Journal* 33 (4): 15–22.

Maheswari, J. U., and K. Varghese. 2005. "Project Scheduling Using Dependency Structure Matrix." *International Journal of Project Management* 23 (3): 223–230.

Masmoudi, M., and A. Haït. 2012. "Fuzzy Uncertainty Modelling for Project Planning; Application to Helicopter Maintenance." *International Journal of Production Research* 50 (13): 3594–3611. ISSN 0020-7543.

Müller, J. R., M. D. I. Siiskonen, and J. Malmqvist. 2020. "Lessons Learned from the Application of Enhanced Function-Means Modelling." *Proceedings of the Design Society: DESIGN Conference* 1: 1325–1334doi:10.1017/dsd.2020.87.

Öhrwall Rönnbäck, A. B., and O. Isaksson. 2018. "Product Development Challenges for Space Sub-System Manufacturers." *Proceedings of the 15th International Design Conference* 1: 1937–1944. doi:10.
21278/idc.2018.0534.

Pedersen, K., J. Emblemsvåg, R. Bailey, J. Allen, and F. Mistree. 2000. "The 'Validation Square'-Validating Design Methods." ASME Design Theory and Methodology Conference, New York.

Shabi, J., Y. Reich, and R. Diamant. 2017. "Planning the Verification, Validation, and Testing Process: A Case Study Demonstrating a Decision Support Model." *Journal of Engineering Design* 28 (3): 171–204.

Shank, J. K. 1989. "Strategic Cost Management: New Wine or Just new Bottles?" *Journal of Management Accounting Research* 1: 47–65.

Sánchez, A. H., T. Soares, and A. Wolahan. 2017. "Reliability Aspects of Mega-Constellation Satellites and their Impact on the Space Debris Environment." Annual Reliability and Maintainability Symposium (RAMS), Orlando, FL. IEEE.

Tahera, K., and C. Earl. 2018. "Testing and PLM: Connecting Process and Product Models in Product Development." In *Product Lifecycle Management-Terminology and Applications*, edited by R. Udroiu and P. Bere, 73–92. London: IntechOpen.

Tahera, K., D. C. Wynn, C. Earl, and C. M. Eckert. 2019. "Testing in the Incremental Design and Development of Complex Products." *Research in Engineering Design* 30 (2): 291–316.

Tatikonda, M. V., and S. Rosenthal. 2000. "Technology Novelty, Project Complexity, and Product Development Project Execution Success: a Deeper Look at Task Uncertainty in Product Innovation." *IEEE Transactions on Engineering Management* 47 (1): 74–87.

Ulrich, K., and S. Eppinger. 2015. *Product Design and Development*. New York: McGraw-Hill Higher Education.

Wang, W., M. H. Azarian, and M. Pecht. 2008. "Qualification for Product Development." International Conference on Electronic Packaging Technology & High Density Packaging, Shanghai, China. IEEE.

Wilson, J. M. 2003. “Gantt Charts: A Centenary Appreciation.” *European Journal of Operational Research* 149 (2): 430–437.

Worldsalaries. 2019. “Engineer Salaries - International Comparison.” http://www.worldsalaries.org/engineer.shtml.

Wu, C. L. 2016. *Airline Operations and Delay Management: Insights from Airline Economics, Networks and Strategic Schedule Planning*. New York: Routledge.

Wyatt, D. F., C. M. Eckert, and P. J. Clarkson. 2009. Design of Product Architectures in Incrementally Developed Complex Products.” In *Proceedings of ICED 09, the 17th International Conference on Engineering Design*, Palo Alto, CA, USA, edited by M. Norell Bergendahl, M. Grimheden, L. Leifer, P. Skogstad, and U. Lindemann, 167–178.

Article E

Fuzzy model-based design for testing and qualification of additive manufacturing

Olivia Borgue [(1)], Massimo Panarotto [(1)], Ola Isaksson [(1)]

(1) Chalmers University of Technology, Chalmersplatsen 4, 412 96 Göteborg, Sweden
Olivia Borgue, borgue@chalmers.se (corresponding author)
Massimo Panarotto, Massimo.panarotto@chalmers.se
Ola Isaksson, ola.isaksson@chalmers.se

ABSTRACT

The uncertainties and variation of AM material properties and its impact on product quality, troubles designers. The lack of experience in AM technologies renders the experts´ assessment of AM components and the establishment of safety margins, difficult. Consequently, unexpected qualification difficulties resulting in expensive and lengthy redesign processes might arise. To reduce the risk of qualification failure, engineers might perform copious time-consuming and expensive specimen testing in early phases, or establish overconservative design margins, overriding the weight reduction benefits of AM technologies. In this article, a model-based design method is proposed for the conceptual design of AM space components with affordable test phases. The method utilizes fuzzy logics to systematically account for experts´ assessment of AM properties variation, and to provide an early estimation of a product qualification likelihood related to design parameters of interest, without the need for copious testing. The estimation of qualification likelihood can also point out which are the unique AM material uncertainties that require further specific testing, to enable the design of a product with a better performance and more affordable test phases. The method is demonstrated with the design for AM gridded of ion thrusters for satellite applications.

INTRODUCTION

Qualification procedures used in the space manufacturing industry aim at ensuring that a product, with its materials and manufacturing processes, meets design requirements [1,2]. For traditional technologies such as forgings and castings and even weld assemblies, general qualification activities are well recognized and standardized. The predictability of final product property variation (regarding, for instance, material defects, microstructure variation, etc..) is generally better than for additive manufactured products.

However, design specifications are less precise in early design phases and are continuously developed as the product development process advances. The uncertainty in design specifications is often accompanied by uncertainties in the manufacturing process, which requires designers to assess from experience and previous data how design choices will impact the qualification process. Casting technologies, for example, present an ample variation of material properties. When designing for casting, however, decades of

experience allow designers to assess in early design phases how material variations might impact qualification and allow them to set experience-based design margins [3].
However, the introduction of novel technologies raises the question on how design and qualification procedures need to be adapted to the new products? The lack of experience about design and qualification procedures for new technologies, can lead to unexpected difficulties in designing a qualifiable product, resulting in expensive redesign processes and schedule delays [4,5]. Such is the case with the introduction of additive manufacturing (AM) in the space industry.
Based on nominal (average) values of material data, AM promises to enable weight [6], lead times and costs reduction [7]. However, the magnitude and interaction of factors that lead to material properties variations, such as material type, process parameters or powder quality, are still not well understood and documented in a way that is applicable for each individual AM design [6]. Unlike casting technologies, in addition to properties variation, the lack of experience in AM technologies complicates the experts´ assessment of AM components and the establishment of design specifications and safety margins [2]. For this reason, products might fail their qualification tests resulting in expensive and lengthy redesign processes [9]. In this context, manufacturers of space components have several options [8]:

1. Develop novel AM designs ensuring their quality through exhaustive statistic-based testing and reliability methods in early design phases to reach sufficient confidence in material data (required by procedures such as failure mode, effects, and criticality analysis (FMECA) [10]), usually involving between 300 and 900 test specimens [11]. Considering that AM mechanical properties are dependent on part geometry, this strategy could lead to cost and schedule overrun if several possible product geometries are considered.
2. Avoid testing many specimens by developing a conservative design based on general AM guidelines [2]. In this way, the manufacturer develops a high-quality product but misses the opportunity of design exploration to develop a more radical and perhaps better design, leading to suboptimal designs with excessive design margins [13].
3. Develop a novel AM design without performing much testing. Such a strategy facilitates design exploration and innovation. However, it is rarely acceptable in critical space applications to date but might be implemented in non-critical “safe-fail” components, (limits design applicability).

Authors such as Seo [11], Karlow Herzog [14] or Mokhtarian et al. [15], recommend a combination of the three strategies, proposing the early implementation of model-based design methods to reduce the number of tests needed and to evaluate the influence of design and process parameters on component quality to establish data-based design margins.
At present, however, there is a lack of methods to overcome the lack of experience about AM technologies and quantitatively include AM uncertainties early in the design loops, to support the development of qualifiable products [2].
Modelling and quantifying the impact of AM process variation on a product´s qualification ability, would support the identification of design features where further testing is required (and affordable) to establish tighter design margins. The classical

approach to reduce uncertainty and variation of materials through test campaigns is found to be too expensive, which is why there is a need to find alternative strategies to assess qualification strategies when designing for additive manufacturing. For this reason, the study presented in this article aims at answering the research question:

RQ: How can AM process uncertainties and their impact on qualification be modelled and included in early design phases?

The attractiveness of AM to offer better design freedom governs the necessity to better know the consequences and possible risks of relying on AM technologies already in the conceptual stages. For safety critical and weight optimized components, qualification is critical, likeliness to successfully qualify the product is decisive.

In this article, a model-based design for qualification method is proposed that aims at supporting the conceptual design of AM components for space applications with affordable test phases. Through the implementation of fuzzy logic techniques, experts´ assessment of AM properties variation is modelled to develop a quantitative metric for qualification ability. The novelty of the method lies on utilizing the quantitative metric for qualification ability to elaborate qualification maps that model the impact of design parameters and their interactions, on a product´s qualification ability. The implementation of qualification maps supports reducing the amount of test specimens, identifying the design parameters where further testing is valuable to establish tighter design margins. Design parameters where further testing is excessively costly or time consuming can be assigned larger design margins.

A detailed design case from the implementation of AM technologies in the manufacturing of satellite propulsion systems is developed to demonstrate the method.

BACKGROUND

Qualification activities are test activities which are performed to demonstrate that a product meets its design, quality, and reliability requirements as well as safety and legislative norms [1, 2]. Similar objectives can also be attributed to the verification, validation, and testing (VVT) activities performed in the systems engineering field [17], moreover, the systems engineering ISO standard 15288 that include processes and lifecycle stages draws a parallel between verification activities and qualification [18].

For already established manufacturing technologies, several qualification standards that guide qualification activities exist. Such is the case of NASA qualification standards for casting NASA-STD-6016 (Materials), -5009 (Non-destructive tests) -5012 (Structures), -5019 (Fracture Control) [19]. According to standards and common practices [16], each qualification test had its own pass/fail criteria determined before the test is performed. In the case of qualification tests to assess component response to environmental loads for instance, a test can be considered failed when the presence of fatigue cracks, excessive structural deformation or instabilities are observed in the component after the test.

The criteria for the evaluation of qualification tests are often identified and formulated from a FMECA (Failure Mode Effect and Criticality Analysis) study [10], where criticality of failure modes is identified and their impact is assessed. Potential failure modes are classified according to their impact on the system and can be utilized to complement, among other things, an assessment of components and subsystems criticality.

In early design phases, product design specifications and associated loads (including those related to failure modes and their criticality) are not completely established and are typically evolved and refined as the product development process advances. The insufficient precision in defined design specifications pose a problem when designing qualifiable products. Designers must assess from experience, early testing activities and previous projects data how design choices will impact the qualification processes [3, 10]. In this context, design development and qualification are performed iteratively during product development; however, design iterations due to failed qualification tests can incur in expensive delays on a product development schedule [5].

Authors such as Pecht [20], Preussger et al. [21], Yadav et al. [22] or Dordlofva and Törlind [3] sustain that to reduce design iterations due to failed qualification tests, qualification procedures and requirements need to be addressed in the early stages of a product development process.

Pecht [20], Preussger et al. [21] and Yadav et al. [22], for instance, have proposed methodologies and guidelines for the electronics industry focusing on reliability assessment, test activities and test planning early in the development process. However, a continuation of their work including guidelines for approaching product design considering how the product should be qualified, is still missing.

FMECA [10] is often included as a mandatory activity within the development process, and since it identifies risks and require mitigation plans, it typically drives design and analysis iterations to reduce uncertainties and reach satisfactory reliability. However, these methods are often criticized since quantifying consequences may require extensive test campaigns, being labor and cost intensive [23]. One reason is the quantitative nature of risk identification, which is often based on experience, whereas the effort to resolve the potential risks can be substantial.

In the work by Dordlofva et al. [5], the authors proposed a method for identifying factors that motivate and influence product qualification, called “qualification drivers”. The identification of qualification drivers is intended to reduce the amount of required testing and support the development of Design for Qualification guidelines and methods. Nevertheless, the authors did not propose qualification guidelines or quantifiable ways to link the influence of design parameters with qualification procedures. Moreover, it is assumed in their method that there is enough information about qualification activities and requirements already in early design phases.

When introducing a new technology, in early design phases the problem related with loosely defined qualification requirements is aggravated with the lack of experience about designing and qualifying a product with the new technology.

Qualification of additive manufacturing components

Although there is a growing interest to introduce AM to reduce weight, cost, and time to market [2, 6], most examples of AM parts that have been successfully developed and implemented in the space industry are non-critical [6]. This means that a failure can be accepted without fatal consequences, and the margins can be narrowed down and accepted. The consequence and criticality of the risks identified in an FMECA are consequently lower for non-critical products. The lack of critical space components manufactured using AM is mostly due to qualification of AM still being a challenge [24], as there is a lack of understanding of AM processes [9] and a lack of standardized approaches to ascertain the quality of AM parts [17]. The statistical spread in properties is not acceptable for critical products.

The need to support engineers early in product development to allow them to explore the design potentials enabled by AM is often highlighted, such design for additive manufacturing (DfAM) methods and strategies have been previously reviewed by authors such as Gibson et al. [12]. However, there is little focus on methods to explicitly support engineers in designing products that can be qualified, especially for critical applications such as satellite components [2, 6].

AM parts exhibit characteristics that are challenging for engineers designing for AM, such as: anisotropic and location dependent material properties, material defects (such as cracks, pores, or lack of fusion), or rough surfaces. It has also been shown that part geometry impacts these material characteristics [24], putting additional responsibility on engineers to understand the capabilities of AM processes, and to design qualifiable AM components. The lack of understanding and previous experience with AM contributes to lengthy and expensive FMECA activities and the development of AM products with ample design margins [13] that might undermine the weight reduction benefits from this technology.

Dordlofva [2] introduced a design for qualification framework for AM that proposes to design a product concurrently with its qualification process. To account for loosely defined qualification requirements in early design phases, the author proposes over dimensioned safety factors, such as those implemented for casting technologies [3, 13]. The author, however, does not provide explicit guidelines to propose those safety factors. In the case of casting technologies, those safety factors are established through data from previous projects and experts´ experience, in AM, however, the lack of knowledge about the technology renders this assessment difficult.

To address the lack of knowledge about AM and to be able to establish those safety factors at the expense of product weight and without performing exhaustive and expensive tests [10, 24], authors such as Seo [11], Karlow Herzog [14] or Mokhtarian et al. [15], recommend the early implementation of model-based design methods [25].

In contrast to design methods based on text descriptions and drawings, model-based design methods capture designs in a model environment for design analysis and simulations purposes, facilitating information sharing and collaboration [25]. Model-based methods can reduce the consequences of AM uncertainties and implement the little data and experience available about AM, to evaluate the influence of design and process parameters on component quality.

Fuzzy logic implemented in the product development process

One type of model-based methods to support problem solving when sources of uncertainty are involved, are fuzzy logic methods [26]. Probability is related to the frequency of occurrence of events, captured by repeated experiments. Fuzzy logic methods, on the other side, provide a framework for evaluating the possibility of events rather than their probability [26].

In fuzzy theory, the possibility of events is represented through fuzzy membership functions. A membership function μA(x) for a fuzzy set A on the universe of X is defined as $\mu A: X \rightarrow [0,1]$. Each element of X is mapped with a membership value between 0 and 1. Each membership function $\mu A(x) \in [0,1]$. If μA(x)=0, it implies that $x \notin A$. On the other hand, if μA(x)=1, then $x \in A$ [27]. The shape of a membership function is adapted to the data it represents [26]. In Figure 1, triangular and trapezoidal membership functions, μ(T), are used to model to people´s perception of different temperatures. At 19 degrees, some people will feel cold (70%), while other will feel warm (30%); at 26 degrees, some people will feel warm (90%) and some other hot (10%). At 15 degrees, everyone agrees that is cold, and on 35 degrees, everyone agrees that is hot (example based on the content of the work by Zimmermann [27]).

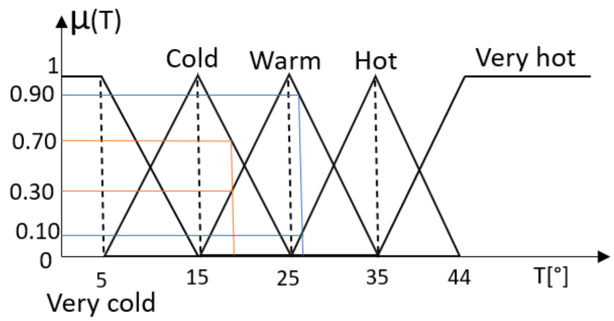


Figure 1. Triangular membership functions modelling people´s perception of different temperatures

One of the main benefits of fuzzy logic is to approximate the behavior of a system when analytic representations do not exist. Hence, they are inherently useful for dealing with complex systems, such as engineering design systems, where multiple inputs and outputs cannot be captured analytically [26].

In this context, one of the most widely implemented fuzzy logic techniques is Mamdani inference [28]. Mamdani fuzzy systems were developed to describe operators´ decisions when controlling processes with a set of linguistic IF-THEN rules, to be then used by a machine to automatically control the same processes [28]. This method is especially appropriate when sophisticated mathematical models are not needed, and where experts' knowledge and experience can be easily included in the model structure [29].

Another widely implemented fuzzy logic technique is Sugeno interference [30]. Its main difference respect Mamdani interference is its outcome; Mamdani interference enables fuzzy outcomes which can be then defuzzified (crisp outcome), Sugeno interference directly provides a crisp outcome. Consequently, Mamdani interference provides a higher expressive power and more nuanced and interpretable results, which makes it a better fit for decision support applications [26, 30].

These characteristics render Mamdani fuzzy logic increasingly attractive for product development applications. The main advantage of these approaches is that they systematically implement experts´ assessments in a quantifiable manner, which is rarely the case on product development processes, as can be found in the work by Saridakis and Dentsoras [31] or Boujour et al. [32]. These authors implemented fuzzy logic for supporting model-based product design activities in early phases. Such studies, however, are not concerned with designing qualifiable products for novel technologies, such as AM.

Other authors [33, 34], have implemented Mamdani fuzzy sets in designing for AM strategies for considering the uncertainty of AM processes outcomes. In their work, Elkaseer et al. [33], for instance, developed a fuzzy logic-based algorithm that mimicked knowledge-based expert systems to automatically take corrective actions to improve printing quality. Lanzotti et al. [34] implemented a fuzzy approach for supporting the evaluation and selection of optimal design concepts where AM alternatives were evaluated. In these articles, however, the insights obtained from the fuzzy logic methods are not fed back to early design stages to improve a design.

Fuzzy logic methods seem to be appropriate to support the introduction of AM technologies in the space industry. These methods can be an asset for modelling AM manufacturing uncertainties without incurring into long and expensive test phases to attain the statistical determination of material properties and probabilistic assessment of qualification risk [35].

RESEARCH METHODOLOGY

An application where qualification impacts and sometimes hinders the implementation of new technologies, such as additive manufacturing, was identified in the context of an advanced manufacturing demonstration program, with the objective of developing the next generation of electric satellite propulsion systems.

In this context, this article is focused on the activities concerning the qualification of a high-power electric propulsion system adopted on interplanetary missions. The focus of the study is the conceptual design of the thruster unit (TU) from an electric propulsion system (EPS) and the design decisions made around its components design when the implementation of AM is intended.

The core of the data collection activities for this study was performed through a three months study visit at a company manufacturer of EPS systems and various satellite components. During that period, the authors worked on site, in close collaboration with the company design team of the present technology program where full access to real design and qualification company data, was provided. Moreover, it enabled continuous interactions with designers while they made real design decisions.

However, the on-site visit was a part of a four-year project, from 2017 to 2021, period where the industrial partners developed and tested the EPSs. The researchers attended the project, prepared the 3 months study and have follow up with the company after the three-month focus study was over.

From the study, a fuzzy model-based method for assessing the impact of design parameters on the outcome of qualification procedures and for including these insights in early design phases, was developed. The method aims at supporting design exploration and design decisions to develop qualifiable products. To illustrate its implementation, the method was applied in a sample case study featuring the redesign for AM of two components in a TU of a propulsion system for space exploration.

MODEL-BASED DESIGN FOR QUALIFICATION FOR ADDITIVELY MANUFACTURED SPACE COMPONENTS

In this section, a model-based design method that supports the affordable introduction of AM technologies in space components, is presented. The method implements fuzzy logic techniques for modelling qualification requirements during conceptual design phases. Fuzzy logic techniques were preferred due to the unpredictable nature of AM defects and their ill-defined influence on product quality [11, 24].

In Figure 2, the proposed method, is presented. The necessary inputs for the method are overall product architecture and test and qualification plan, a datasheet of the components intended to be redesigned for AM and general AM design guidelines [12, 36].

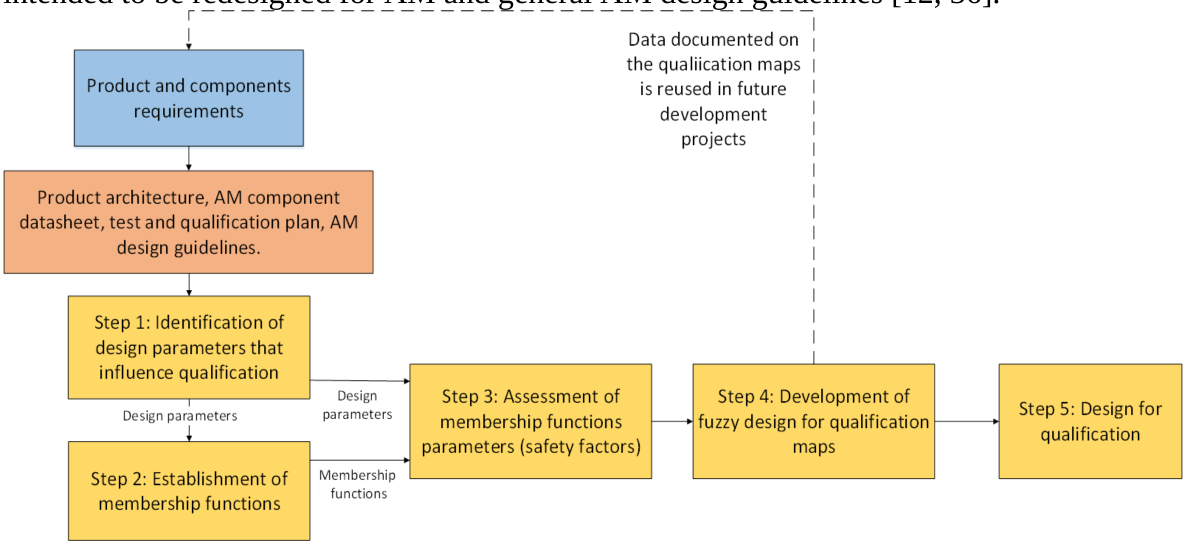


Figure 2. Model-based method for design for qualification

Step 1: Identification of design parameters that influence qualification

In this step, component design parameters that can affect the outcome of qualification activities (pass/fail) are identified. Due to the additive nature of AM technologies, design parameters can influence the presence of unexpected material defects, microstructure variations or geometrical deformations (among others) that might have a negative influence in the qualification processes. The stair stepping effect observed in angled surfaces, for instance, is the main cause of low surface quality [14]. If a component requires a specified surface roughness, qualification activities will be performed to ensure compliance with this design requirement. If the surface cannot be treated to improve its surface finishing, surface inclination angle is a design parameter that can influence the outcome of qualification activities. Such case is presented in depth in the work by Dordlofva [2], when designing the untreatable internal surfaces of a manifold for a rocket engine.

Step 2: Establishment of membership functions

Each design parameter identified in Step 1, is assigned a membership function whose shape should be chosen to fit the design parameter data set. In Figure 3, an example of how the shape of a membership function is established is presented.

In Figure 3, the membership function $\mu(\alpha)$ for the surface inclination angle, α, and its influence on the outcome of the qualification tests is trapezoidal, and obtained from the Root mean square height, Arithmetical mean and Maximum peak height data. High surface quality is achieved in completely horizontal (90°) and vertical surfaces (0°) [14]. The worst surface roughness seems to be obtained from a range of angles that starts at ~30° and covers angles up to ~70° (three graphs from Figure 3, top). If the component requires a smooth surface, after a certain threshold angle (around 30°), there is a range of angles where the surface becomes too rough (~30° to ~70°), resulting in a failed qualification test (red area in Figure 3, bottom). Angles below ~30 and above ~70 are more likely to result in a high likelihood of a successful qualification.

Design requirements would determine which surface roughness range are acceptable and which are not, which is essentially the establishment of the membership function parameters α2 and α3, from Figure 3 (red zone). Due to the complex physical phenomena taking place in AM and the sometimes-unpredictable nature of the manufacturing outcome [2, 9, 37], surface angles lower than α2 and higher than α3 might still present rough surfaces and compromise component compliance with qualification requirements. Some α values might result in a failed qualification test but might also result in a successful one (orange zone).

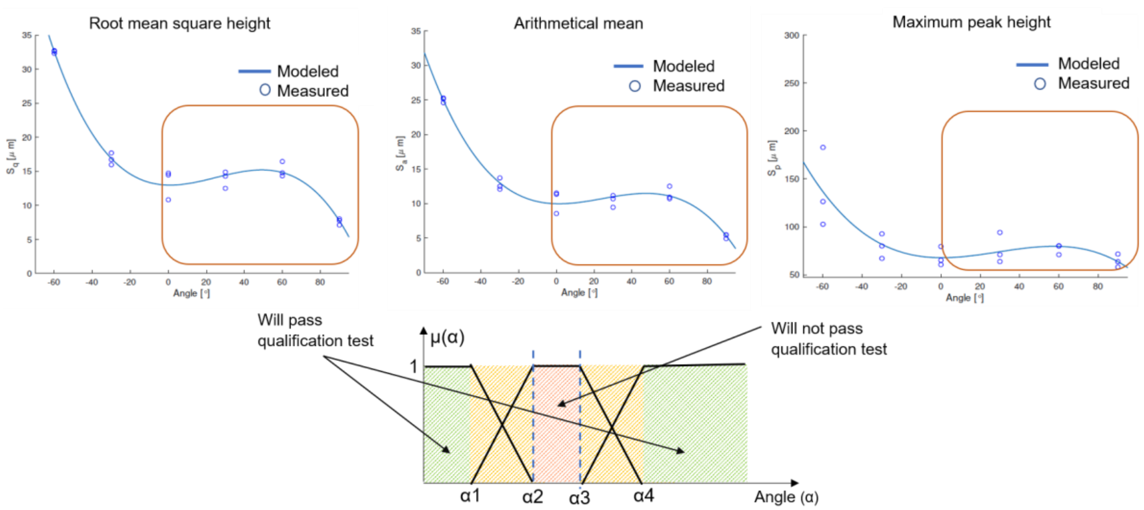


Figure 3. Top, surface roughness data [14]; bottom, membership function

Step 3: Assessment of membership functions parameters

When a membership function is selected for each design parameter, the membership function parameters must be established. In this step, design specifications are assessed to determine when x ∈ A (μA(x)=1) and when x ∉ A (μA(x)=0).

For aerospace grade metallic materials, the qualification procedure for introducing a new alloy is rigorous [11]. Minimum design values that should be considered as membership function parameters are based on component criticality and established through thorough statistical procedures. Critical, non-redundant structures usually require A-Basis minimum values, where the minimum data requirement for material properties is around 300 samples for an isotropic material and 900 samples for anisotropic materials. Although, the amount of testing required to fully define the mechanical behavior of the material (both static and dynamic perspectives) might require thousands of individual tests [11, 35]. This rigorousness, however, delays time to market, increases costs, and hinders innovation and the introduction of new technologies to aerospace components

[35]. Currently, if two different manufacturing processes for the same material are used to manufacture a component, current practices treat them as two different materials because the microstructures cannot be proven to be identical [35]. In the case of AM, mechanical properties and microstructure are also dependent on part geometry [24], which requires different geometries to be treated as different materials during the material qualification processes. Such rigorous test strategies might not be affordable in scenarios where design exploration is desired.

An alternative pathway for the thorough statistical procedures is using experts´ opinions for establishing membership function parameters. A similar approach was proposed by Dordlofva [2] in the study of the AM manifold, where overconservative AM safety factors were determined by company practitioners. In this context, the determination of the membership functions parameters is closely related with the determination of AM safety factors, which can be established with an assessment of available AM inspection methods or post-processing techniques. Moreover, the assessment of these parameters can be related to qualification schedule and cost. If the component under analysis is part of the critical path of the general product qualification activities, stringent parameters can be applied to reduce the risk of failing qualification tests and incurring in redesign procedures that can delay overall product qualification.

Since experts´ experience is in general vague and hard to capture, a Multi-Expert Multi-Criteria Decision Making (ME-MCDM) fuzzy approach, is implemented [33] in this step. The proposed ME-MCDM fuzzy approach, is supported by an Ordered Weighted Average (OWA) technique [38], for combining different experts´ opinions. This approach has been successfully tested by authors such as Saridakis and Dentsoras [28] and Lanzotti et al. [33].

As the quality and reliability of their assessments depends on the experience of each expert [39], they provide their opinions in the shape of fuzzy sets which are then weighted according to an established weighting system. These fuzzy sets are proposed (before the weighting process) as triangular functions which can be interpreted as a main parameter value (triangle top vertex) considered with a certain error defined by the lateral triangle vertices. Their opinions are aggregated and then defuzzified following equation (1) [26, 27, 31], which represents the centroid of all the considered fuzzy sets:

$$centroid = \frac{\int x * \mu A(x)}{\int \mu A(x)} \qquad (1)$$

Where $\mu A(x)$ is the membership function value for x .

If a specific x has more than one membership function associated, the equation considers the value of the $\mu(x)$ function with the highest value.

There are numerous defuzzification methods, and their selection is context dependent. For this study, the centroid method was preferred due to its popularity and computational convenience when defuzzifying simple membership functions, however, other methods might yield similar results [26, 27].

Following the surface roughness example, three experts would evaluate each membership function parameter $\alpha 1$ and $\alpha 2$, providing an error margin in their estimations. The designers have weights of (0.9, 0.8, 0.6) according to their experience in the field in design for additive manufacturing. In Figure 4, each designer´s fuzzy set (identified with different shades of blue) is presented for the parameters $\alpha 1$, $\alpha 2$. The sets are cut at levels corresponding to their opinion weighting. The area formed by all the fuzzy sets after the weighting process is then defuzzified finding the centroid of the formed area with equation (1).

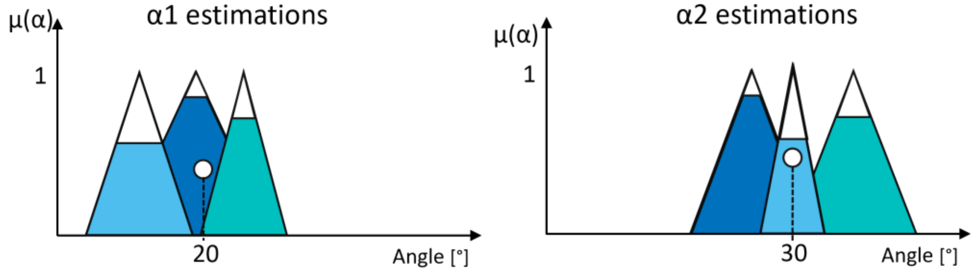


Figure 4. Fuzzy sets from three experts (different shades of blue) to obtain parameters α1, α2 to be used in the membership function for assessing surface inclination and its effect on qualification

Step 4: Development of fuzzy design for qualification maps

Having established the parameters of every membership function, those functions can be combined to create qualification maps, as the one exhibited in Figure 5. In Figure 5, the combination of the parameters α (surface inclination angle) and τ (wall thickness), and its impact on likelihood of a successful qualification test, is presented.

Qualification likelihood for α, $\mu(\alpha)$, is added to qualification likelihood for τ, $\mu(\tau)$, creating a three-dimensional plot of qualification likelihood (evaluated from 0 to 1), α and τ. Every point in the plot is defined by the value $[\alpha , \tau , \mu(\alpha) + \mu(\tau)]$, the qualification likelihood is then scaled to provide values from 0 to 1.

These qualification maps map the design space according to their likeliness to pass qualification tests. In the surface roughness example, $\mu(\alpha)$ is mapped against a $\mu(\tau)$ which represents the possibility of failing a qualification test depending on the wall thickness, τ. Both thin walls and rough surfaces are in high risk of failing the qualification tests. The combination of the two, reduces qualification likelihood even further.

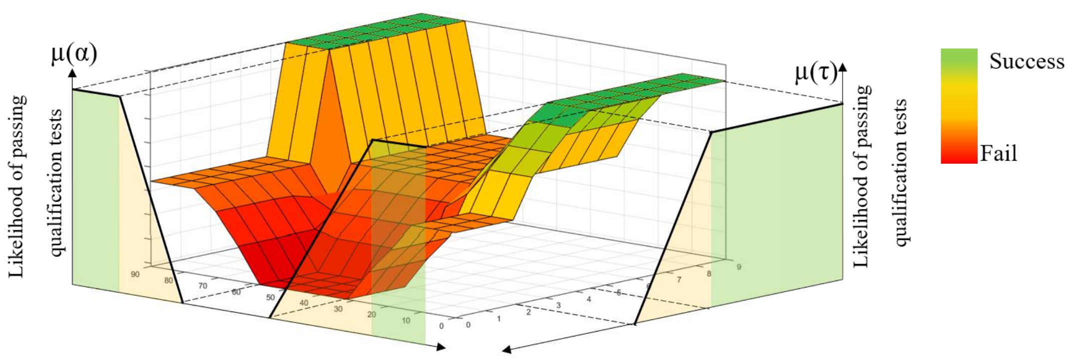


Figure 5. Qualification map for two generic design parameters α and τ

Step 5: Design for qualification

The qualification map helps the visualization of design alternatives and their assessment regarding qualification. It can be used, for example, in a multidisciplinary design trade-off analysis to compare different product concepts. The map, however, is intended to be a dynamic tool, a way for designers to assess which parameters combinations can result in qualifiable products and then use that information when comparing alternative designs and making design and test related decisions. If a design alternative is superior to others in some ways but it is located in an orange zone in a qualification map, it is an indication that the design might not pass a qualification test. In this case, extra material testing activities can be performed to redefine that specific orange zone and perhaps, reduce the distance between α1 and α2 or α3 and α4. In this case, the qualification map indicates where it is worth it to perform extra testing and where it is not. This feature enables the development of a design exploration strategy for the development of a high-quality product, while reducing the test phases related to the material qualification of numerous different geometries.

Different companies and different products with the same design parameters (such as α or τ) will likely have different membership function parameters (different α1, α2, α3 and α4) due to the variability of human assessment and the variation of component requirements among companies. This fact suggest that a qualification map can support questioning the established design specifications and AM safety factors (is it necessary to have such a smooth surface?), as they are not inherently fixed.

AM data obtained from the implementation of the proposed model can be formalized and documented in the qualification maps, or in various design/documentation platforms such as those proposed by Borgue et al. [8] and be reused in future development projects.

MODEL-BASED DESIGN FOR QUALIFICATION OF ADDITIVELY MANUFACTURED GRIDDED ION THRUSTER COMPONENTS

In this section, the developed model-based design for qualification method is implemented in the redesign for AM of two components of a TU in a gridded ion thruster with an approximate diameter and height of 20 cm and 12 cm respectively. A CAD model of the TU is presented in Figure 6. A thorough description of the functionality of a TU can be found in Kindberg [40].

The anode and the external shell are intended to be redesigned for AM. In the anode, the propellant is ionized and then accelerated. This component requires a smooth internal surface and is machined from a metal block to form the anode geometry. The anode is usually in contact with the ”screen grid”, the first grid of a series of three acceleration grids [40].

The external shell, on the other side, encloses the internal TU circuitry and provides a general protective function. This component is manufactured with soft iron.

Redesigning these two components for AM can reduce component weight, to satisfy industry requirements for cost efficient space systems [36, 41], and overall manufacturing costs, as AM processes can reduce costs of tooling and machining and require less skilled labor forces [7].

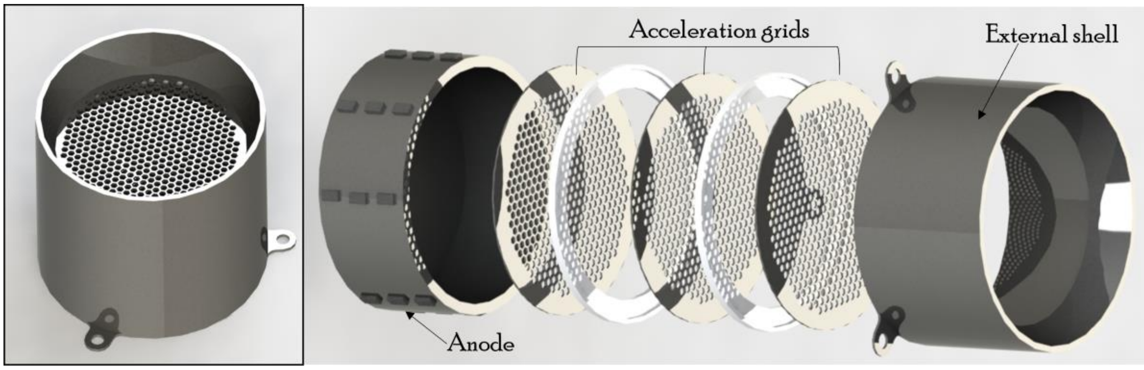


Figure 6. CAD model of a gridded thruster. To the right, chamber and shell to be redesigned for AM

Using design for AM guidelines, such as those proposed in literature [12, 36]. The shell is redesigned for AM with the inclusion of diamond-shaped holes in the protective walls (Figure 7.a), to reduce its overall weight. In this design, three parameters can influence qualification: wall thickness, number of diamond-shaped holes and separation between holes.

The presence of AM defects such as pores, lack of fusion or cracks can lead to catastrophic failure of thin AM walls and clustered holes [37, 42]. Moreover, Saneai et al. [37] reported that surface proximity can negatively influence defect size and density, which can affect functionality (or the outcome of a qualification test) in a component with a large number of surface holes.

The AM anode design is optimized including a curved bottom (Figure 7.b.) and is designed to be integrated with the screen grid. This integrated design is based on two parameters that can influence the outcome (pass/fail) of qualification procedures: grid wall thickness τ, and angle of the anode wall α. The anode thickness is not modified as is a component from the magnetic circuit and is designed to carry the magnetic flux from the magnets.

The surface inclination angle in the anode will affect the component orientation in the building chamber to avoid internal support structures. Rough surfaces (product of stair stepping effects [14] from various component orientations in the building platform) in the outside surface of the screen grid can enable arcing between this grid and the next one. If the grid is too thin, those surface defects cannot be machined out.

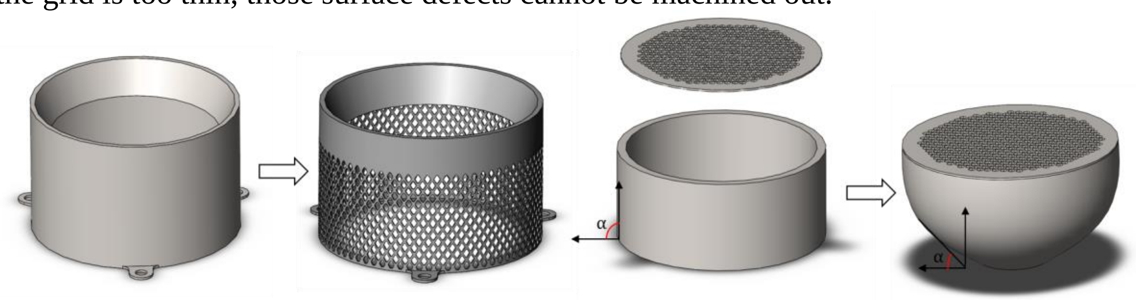


Figure 7. External shell and anode to be redesigned for AM

For supporting design exploration and decision making regarding the design parameters, the proposed model-based design method is implemented.

In Figure 8, fuzzy membership functions for the design parameters that influence qualification outcome for the shell and the anode, are presented. In the case of the protective shell, there is no number of holes that ensures a successful qualification, therefore, μ(N) contains only orange and red zones. The orange and red qualification map is not necessarily a “showstopper”, is just an indication that future qualification problems might arise in the orange zone. With this information designers can different strategies such as eliminating holes, increasing design margins or strengthening the external shell with an additional component.

In the case of the anode, when the surface inclination angle increases there is the possibility of sandblasting the surface to improve its roughness. However, rougher surfaces in the outside of the grid would need larger proportions of its thickness removed, which can result in compromising structural integrity.

Implementing a ME-MCDM [31] fuzzy approach, a panel of experts negotiates the parameters of the membership functions introduced in Figure 8 (the starting points of the different color zones). As Dordlofva [2] proposed, their assessment should be based on three pillars:

- Current relevant material data.
- Additional AM safety margins
- Process control and inspection

Relevant material data and process control can be performed through the implementation of product tailored test artefacts [2], to evaluate the influence of geometry and process parameters on the manufacturing outcome. As AM mechanical properties are geometry dependent [24], the combination of experts´ assessment and product tailored test artefacts is intended to identify which geometries should undergo a more rigorous test process (statistical analysis), reducing in the end the number of test specimens. Insights on how to design tailormade test artefacts can be found in the work by Borgue et al. [8]. With an OWA technique [38], the different experts´ assessments are combined.

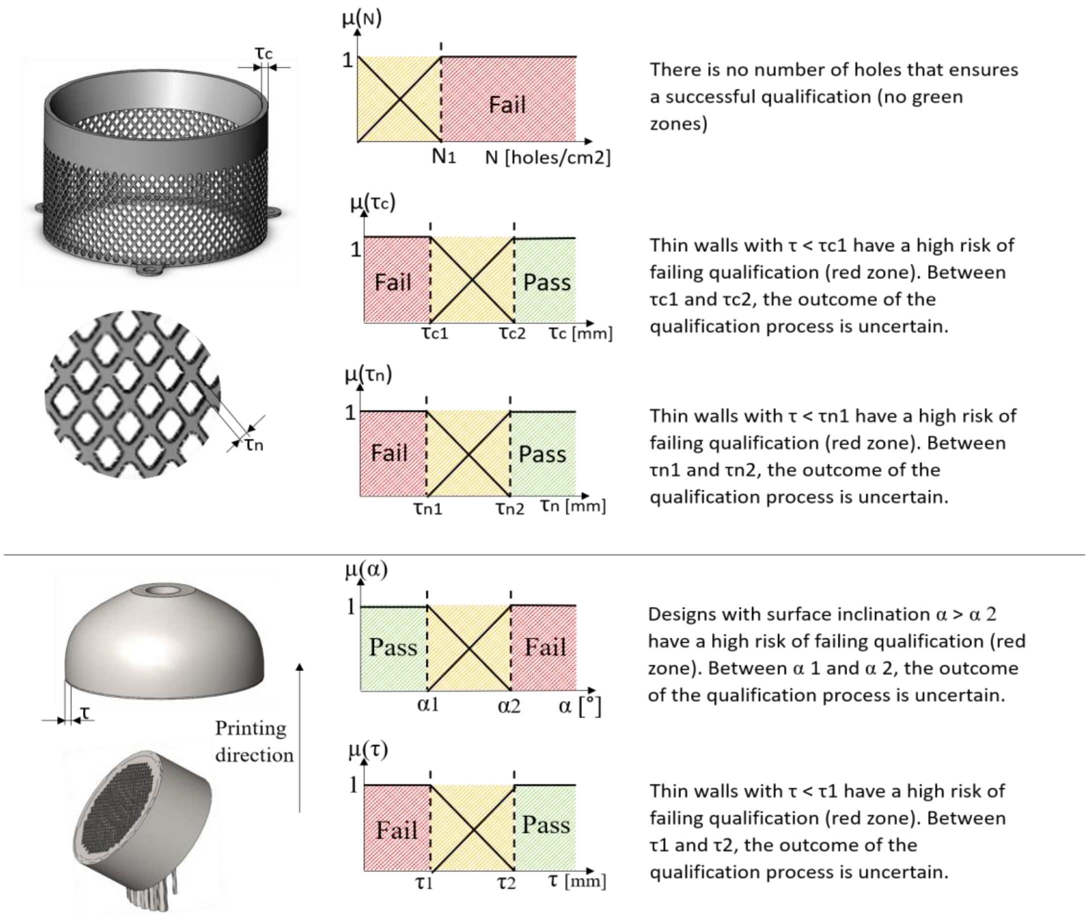


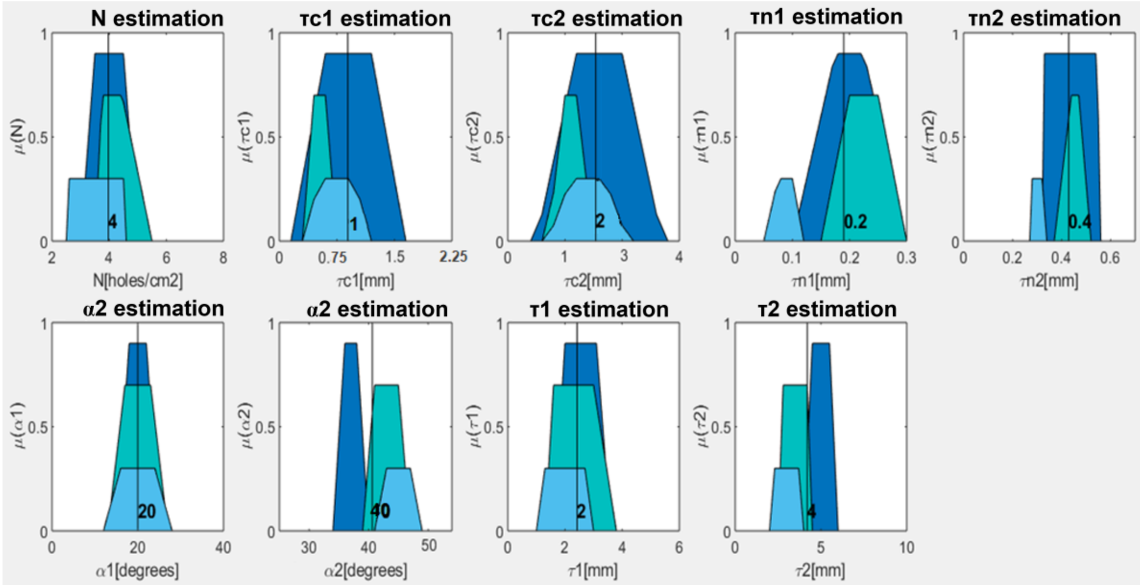
Figure 8. Membership functions for design parameters that can influence qualification outcomes

The weights assessment is context dependent and reflects the perhaps subjective importance or experience of each expert regarding design, qualification, or AM. Experts´ assessments are then defuzzified for determining the membership functions parameters, implementing the centroid equation (1) and exemplified in Figure 9. On the top of Figure 9, experts´ assessments for the membership functions parameters presented in Figure 8 for the external shell (number of holes N, and thicknesses thao τc1, τc2, τn1 and τn2) and for the anode (inclination angles α1 and α2, and thicknesses thao τ1 and τ2) are presented.

The parameters values according to the different experts are summarized on a table at the bottom of Figure 9. For obtaining the parameters values for the qualification maps, the MATLAB built-in methods for Mamdani fuzzy inference system defuzzification were implemented. The centroid was obtained through equation (1) with an error obtained considering on the outmost values provided by the experts. The table results are summarized below:

External shell: N= $4.0^{+1.8}_{-1.8}$ holes/cm2; τc1= $1.0^{+0.7}_{-0.7}$ mm; τc2= $2.0^{+1.7}_{-1.5}$ mm; τn1= $0.20^{+0.10}_{-0.15}$ mm; τn2=$0.40^{+0.15}_{-0.15}$ mm

Anode: α1=(20^{+8}_{-8})°; α2=(40^{+9}_{-5})°; τ1=(2^{+2}_{-1})mm; τ2=(4^{+2}_{-2})mm



Component	Parameter	Expert 1	Expert 2	Expert 3	Centroid
External shell	τc1	(0.30, 1.25, 1.70)	(0.50, 0.65, 0.72)	(0.50, 0.75, 1.30)	$(1.00^{+0.70}_{-0.70})$ mm
	τc2	(0.5, 2.3, 3.7)	(0.6, 1.8, 3.2)	(0.6, 1.1, 2.0)	$(2.00^{+1.70}_{-1.50})$ mm
	τn1	(0.15, 0.25, 0.28)	(0.05, 0.08, 0.12)	(0.15, 0.24, 0.30)	$(0.20^{+0.10}_{-0.15})$ mm
	τn2	(0.33, 0.45, 0.58)	(0.28, 0.30, 0.32)	(0.34, 0.48, 0.52)	$(0.40^{+0.15}_{-0.15})$ mm
	N	(3.0, 4.0, 5.0)	(3.8, 4.1, 5.8)	(2.2, 3.8, 4.6)	$(4.00^{+1.80}_{-1.80})$ holes/cm2
Anode	α1	(15, 20, 26)	(14, 20, 26)	(12, 20 , 28)	$(20.00 +^{+8.00}_{-8.00})$ degrees
	α2	(35, 37, 40)	(38, 42, 47)	(42, 44, 49)	$(40.00^{+9.00}_{-5.00})$ degrees
	τ1	(1.8, 2.5, 3.8)	(1.3, 2.2, 4.0)	(1.0, 2.0, 3)	$(2.00^{+2.00}_{-1.00})$ mm
	τ2	(4.0, 5.0, 6.0)	(2.0, 3.5, 4.5)	(3.0, 3.5, 4.0)	$(4.00^{+2.00}_{-2.00})$ mm

Figure 9. Membership functions parameters assessment with their calculated centroid. Each expert provides their assessment through a central value with error margins.

The main objective when redesigning these two components for additive manufacturing is reducing costs, lead times [7], and component weight [41].

In Figure 10, qualification maps for the chamber and shell are presented. The maps were build utilizing the MATLAB Fuzzy logic designer. On the maps from Figure 10.a, the colored scale from green to red represents the increase in likelihood of failing qualification tests, related to different component design parameters. The maps support the visualization of design parameters interaction and the impact of this interaction on the outcome of the qualification activities as well. In the case of the external shell, when μ(τ) is isolated there is a range of values of τ that are likely to pass a qualification test (green zone). Nevertheless, when μ(τ) interacts with μ(N) there is no value of τ likely to pass a qualification test, as there is no green zone in the qualification map. In Figure 10.b error bands for the horizontal variables are indicated, these bands express the uncertainties related to AM procedures and can enable a rapid identification of robust design alternatives where the uncertainties about AM technologies are low (outside the error bands). Vertical error bands were omitted to not clutter the figure.

As indicated in Figure 10.c, a blue color-coded mapping of the achievable weight reduction percentages is included as well.

In the case of the anode, there is one zone (dark green) in the qualification map that represents the lowest risk of failing qualification tests (9mm-4mm; 0°-20°). A concept design located in this area has a 46% reduced weight, Concept A. Pursuing the design of Concept A, would not require extra testing. On the limit between the light green zone and the yellow zone the percentage of weight reduction reaches 55% with high chances of passing qualification tests.
Further increasing α and reducing τ can end up in 72% weight reduction (center of the dark orange zone), however, the risk of failing a qualification test is high, due to the established overconservative AM safety margins.

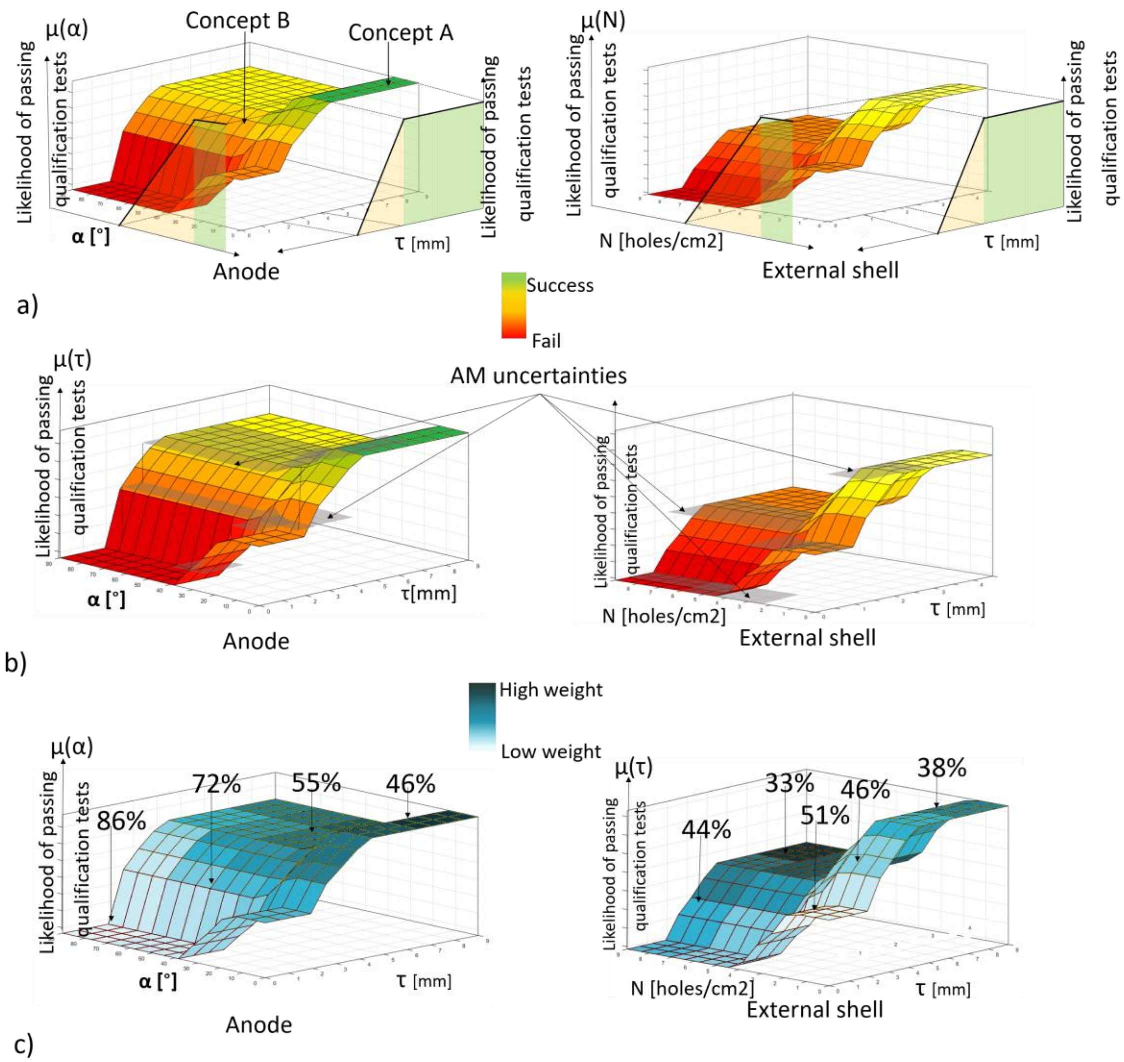


Figure 10. Qualification maps and weight reduction percentages for shell and anode

As Figure 10.c suggests, if a Concept B would aim for a weight reduction beyond 55%, specific material tests with test artefacts [2] can be performed to better define α2 and τ1 and τ2 and hopefully reduce the AM safety margins. As the preliminary selection of these parameters was overconservative, further testing can stretch those limits (increasing the size of the green zones) providing material testing information where is needed.

Similar analysis can be performed contesting qualification likelihood against other requirements such as, for example, manufacturing costs reduction. Moreover, qualification likelihood can be included as a parameter in a multidisciplinary design trade-off analysis, assigning requirements weight according to specific design contexts. In Figure 11, a parallel coordinates [43] example is presented to illustrate qualification likelihood in a design trade-off analysis with requirements about weight, post-processing time and manufacturing time for the integrated anode-screen grid. This multidimensional representation can be used for evaluating the influence that design parameters such as wall thickness, τ (lines with different colors, from 1mm to 7mm), and inclination angle, α, have on different design specifications, including qualification likelihood. On Figure 11, there are several lines with the same colors (same values of τ), these lines represent the different values of α for the same value of τ. Post processing costs are a function of post-processing time and post-processing resources (such as manpower or tools). Manufacturing time costs are a function of manufacturing time (machine set-up and printing) and resources (such as manpower, materials, or electricity).
For the external shell, the highest weight (51%) reduction is obtained with a small number of holes (N) and a thin separation among them. The attainable weight reduction with the lower risk of qualification fail is around 38% (yellow zone). On the orange zone (with a thinner separation among holes), however, the weight reduction possibilities are 8% higher. As recommended for the anode, further tests can be performed with test artefacts to try stretch the yellow area and increase low-risk and low-weight possibilities.

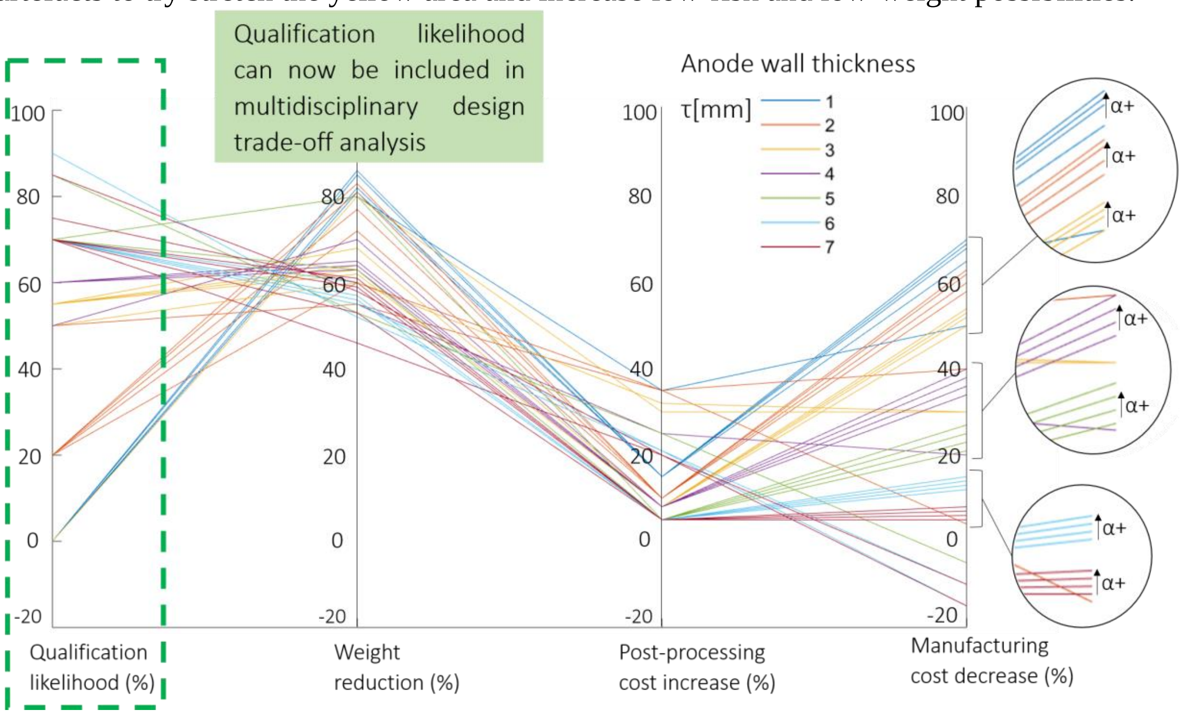


Figure 11. Qualification likelihood can be included in trade-off analysis such as parallel coordinates

Nevertheless, other strategy for enlarging the yellow area in the qualification map is to relax the requirements of the shell as a structural component and transfer those requirements to another component.

In Figure 12, a new qualification map with an extended yellow zone for the shell is presented. This extension was obtained relaxing the structural requirements on the shell (reducing τ1 and τ2) by introducing a new component whose function is to strengthen and reinforce the shell structure. It is now the assembly of the shell and its reinforcement what protects the internal TU component. The dimensions of the reinforcement component are closely related with those of the shell to ensure that the assembly can fulfill its structural requirements. For that reason, to obtain the qualification likelihood of the assembly, the design parameters of both components should be included simultaneously in qualification maps.

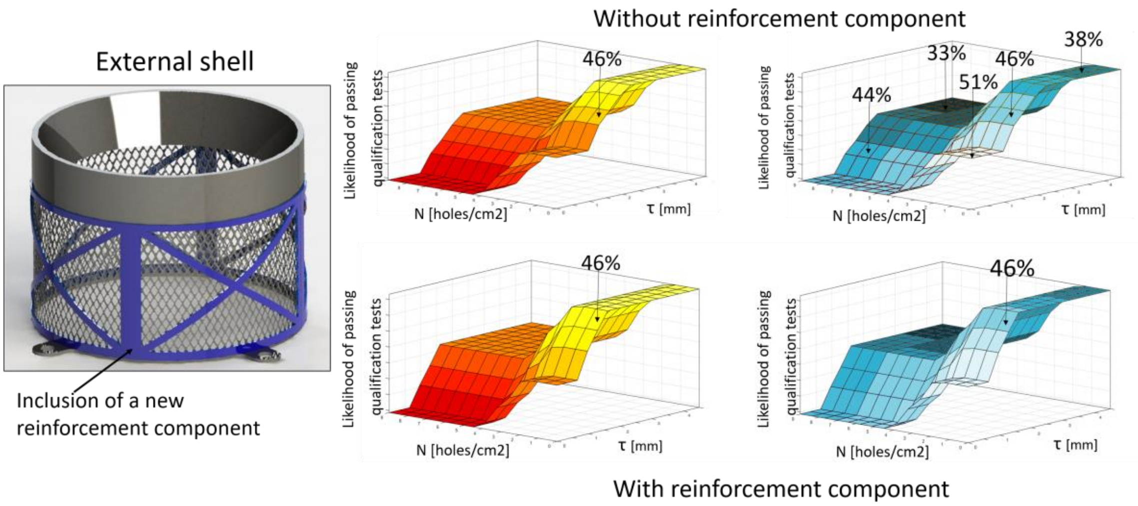


Figure 12. Relaxation of shell structural requirements with the introduction of a support component

DISCUSSION

The main contribution of this study is a model-based design for qualification method and its capability for enabling designers to better account for qualification risk when including AM technologies in the design of space components.

The proposed design for qualification method enables the implementation of qualification metrics as another design requirement in trade-off analysis through strategies such as parallel coordinates assessments [43] or trade-off curves [44] to support the design of affordable and qualifiable products.

The introduction of qualification metrics in trade-off studies is enabled by applying fuzzy logics techniques to model experts´ assessment of AM properties variation, and quantifying in early design phases, the effect that design parameters have in a product´s qualification ability.

Some combinations of design parameters have a rather predictable qualification outcome, for example, designs with extremely thin walls will fail a structural integrity qualification test. For some combinations of design parameters, however, the qualification outcome is uncertain.

In addition to product qualification uncertainty, the dependency of AM mechanical properties on product geometry generates material qualification uncertainties that can affect the design exploration processes. In conventional design scenarios, material uncertainties are solved by extensive material qualification phases to gather statistically significant data about numerous product geometries [11, 35]. If this process would include design space exploration it would be prohibitively expensive because every different geometry should undergo a material qualification testing phase (300/900 samples) [11, 35]. For this reason, material qualification is performed once and the data generated "fix" the materials, processes and geometry constraining design exploration and innovation [35].

In this article, fuzzy logics are implemented to complement probabilistic assessments of qualification failure and enable design exploration. The experts´ assessment and the qualification maps support design exploration previous to material qualification phases with the objective of identifying geometries that should undergo material qualification analysis.

The proposed used of fuzzy techniques for quantifying experts´ assessments in conceptual stages provides a less precise assessment of the possibility of qualification failure. However, at such early phases this unprecise model and assessment might be enough, such was the case of Concept A, or concepts with over conservative safety margins. This result resonates well with authors such as Seo [11], Karlow Herzog [14] or Mokhtarian et al. [15], which sustain that through model-based design methods, relevant decisions can still be made even with unprecise models and information.

To avoid overconservative AM safety margins, however, the use of qualification maps (built through fuzzy techniques) enables the identification of design concepts where these safety margins can be reduced (Concept B), through test campaigns and a more precise and probabilistic assessment of the manufacturing process and its impact on qualification failure. This feature was highly valued by the practitioners as large design margins result in sub optimized heavy products.

This way, fuzzy logic techniques are a complement, rather than a replacement, to probabilistic assessments techniques.

The design for qualification method addresses the uncertainties between design parameters and their incidence on qualification failure. However, these uncertainties are the consequence of the uncertainties from the manufacturing processes, due to the current AM lack of knowledge. For instance, to enable major weight reductions for Concept B, test campaigns and a more precise and probabilistic assessment on how manufacturing process affects the parameters $\alpha2$ and $\tau1$ and $\tau2$ must be performed. Therefore, the second contribution of this article is the identification of the process uncertainties that require immediate clarification.

Contrary to what happens when implementing conventional design analysis methods, fuzzy logics emphasizes uncertainty through "degree of membership" (abscissa values between 0 and 1). This feature was recognized as a reflection enabler, allowing designers to grasp the magnitude of the impact qualification uncertainty has on the design process. Moreover, it enables collaboration among designers, helping them to look over their own aggregated judgements, discuss the accuracy of their first assessments and plan for eventual test phases. These statements are in line with literature findings [28, 31, 33]

Qualification maps analysis can not only support the design activities around singular components (in this case, anode, and external shell) but can transcend components parameters and influence a more general product architecture design. Such is the case for the external shell design, where an additional component was introduced to provide a failsafe mechanism and relaxing the structural requirements on the shell, enabling the design of a lighter component.

In several space manufacturers, design and testing activities are conducted by different departments. Experts stated that the presented design for qualification method can facilitate communication between these two departments, as qualification maps can serve as boundary objects. Moreover, as qualification maps can support both component and product design, as well as test activities (through suggesting test artefacts targeting specific design parameters), they enable concurrent product and test activities design. Practitioners identified this fact as particularly interesting when introducing new technologies, where test phases might be ill-defined, which suggests that the proposed method could be applied to other manufacturing technologies. Moreover, the acknowledgement and inclusion on the maps of the uncertainty (or error) bands, facilitates a rapid assessment of parameters combinations that provide robust design alternatives.

After presented to several practitioners with experience from both design and qualification of AM in critical components, the proposed method, was deemed adequate for generating qualification metrics and allowing qualification risk to be integrated in design studies.

These capabilities have a high potential for reducing the overall cost and duration of test phases.

Moreover, the implementation of the proposed method is expected to require a negligible among of time and resources (in the overall schedule of a product development process) for its implementation. In regular design scenarios, experts are engaged and asked to provide their comments during design phases, this process, however, is yet not formalized. The method in this article proposes a way to formalize these types of discussions with experts. The method would require a short training (an hour or two), whereafter the experts can easily express their comments as parameters to the model instead. As it addresses experience-based opinion no extra time is expected.

However, this claim has yet to be proven, furthermore, the proposed method has not been validated. The validation of the design for qualification method is the subject of another study, where the usefulness of the method is put under scrutiny following guidelines from authors such as Pedersen et al. [46]. For a reliable validation process, emphasis is put on evaluating that the method yields the promised results (a reduction of costs and duration of test phases, while designing a qualifiable product), and that the results obtained are related to the method application and not to other factors.

The proposed method utilizes a general modelling strategy; therefore, it can be inferred that the method can be generalized and applied to various design contexts and novel technologies. A further assessment of the method’s generalizability is, however, still required and part of the future validation studies.

On that note, the method has several limitations:

1- The method addresses the uncertainties between design parameters and their incidence on qualification failure. However, it does not provide a strategy for identifying which are the design parameters with an uncertain impact on qualification. In fact, their identification largely depends on the practitioners´ experience. Some parameters might be easier to identify, as they are well-known as having an impact on qualification, such as wall thickness. Nevertheless, other parameters that influence qualification outcomes might be unknown, and designers might not be aware of them (unknown uncertainties, also known as "unknown unknowns" [47]). Elicitation techniques for unknown uncertainties, such as those found in the work by Sutcliffe and Sawyer [47], could be a complement for the method proposed in this article.

2- The identification of design parameters of interest depends on the practitioners´ experience with design, qualification and AM. Additional training efforts on the necessary topics are recommended for unexperienced practitioners. The method itself can also be interpreted as a training tool; as the method is applied, and knowledge about AM increases, the method meaningfulness and accuracy are expected to improve.

In an industrial context, the proposed method would enrich the conceptual stages with qualification risk assessments and could be a valuable complement to digital parametric designs or abstract product representations such as function modelling techniques [8]. The method proposed in this article can be also complemented and enriched through a connection with qualification schedules. The qualification likelihood obtained from the qualification maps can be utilized as a metric for "activity rework likelihood" or schedule risk [48] to be included in the qualification schedule calculations, to account for the possibility of design iterations. Linking the design for qualification method to parametric product representations and qualification schedules enables the assessment of the impact of design parameter on qualification likelihood and consequent qualification schedule and schedule delays.

CONCLUSION

In this article, a model-based design for qualification method, is proposed. The method is based on fuzzy logic for modelling AM process uncertainties and developing qualification maps for supporting designers to develop qualifiable products.

The novelty of the method lies in the modelling and quantification of qualification risk and its integration into design studies and concept evaluation.

In regular design scenarios, when introducing new technologies in the space industry, hundreds of samples are tested to achieve strong statistical knowledge bases before design and qualification phases. However, as AM material properties are geometry dependent, this process can become time and resource consuming if design exploration is desired.

In this study, experts´ assessments and qualification maps are combined to facilitate design exploration and the identification of product geometries that should undergo rigorous material testing, reducing the time and cost spent in test activities, still ensuring the development of a qualifiable product. Indicating which design parameters combinations yield qualifiable products, qualification maps were proven to support design activities for single components, and for product assemblies as well. Moreover, qualification maps allow designers to look over their own aggregated judgements and discuss the accuracy of their first assessments.

This goes beyond what other studies have reported, enabling qualification to be included in sensitivity studies, trade off studies and other digital experiments where a range of concepts need to be simultaneously evaluated.

A major limitation of the method is its reliance on experts´ assessments (and therefore, their experience with AM). Unexperienced practitioners might face difficulties identifying design parameters that impact qualification likelihood and developing accurate membership functions for those design parameters. Additional AM training might be required and could be supported by the method itself.
The method has been demonstrated for the redesign for AM of the anode and protective shell of a gridded ion thruster for satellite applications. However, a further validation of the method's generalizability is required and left for future research activities in this domain.

ACKNOWLEDGMENTS

-

FUNDING

-

REFERENCES

[1] ISO, 2008, *ISO/IEC 12207:2008 [ISO/IEC 12207:2008]*, Systems and software engineering — Software life cycle processes ISO/IEC 12207:2008, Retrieved from: https://www.iso.org/standard/43447.html

[2] Dordlofva, C., 2020, "A Design for Qualification Framework for the Development of Additive Manufacturing Components—A Case Study from the Space Industry,", Aerospace, **7**(3), 25, https://doi.org/10.3390/aerospace7030025.

[3] Dordlofva, C., and Törlind, P., 2018, "Design for qualification: A process for developing additive manufacturing components for critical systems," *DS 91: Proceedings of NordDesign 2018*, Linköping, Sweden, 14th-17th August, ISBN: 978-91-7685-185-2.

[4] Engel, A., and M. Barad., 2003, "A methodology for modeling VVT risks and costs," Systems engineering **6**(3), pp. 135-151, https://doi.org/10.1002/sys.10040.

[5] Dordlofva, C., Borgue, O., Panarotto, M., and Isaksson, O., 2019, "Drivers and guidelines in design for qualification using additive manufacturing in space applications." *In Proceedings of the Design Society: International Conference on Engineering Design*, Cambridge University Press, **1**(1), pp. 729-738, https://doi.org/10.1017/dsi.2019.77.

[6] O'Brien, M. J., 2018, "Development and qualification of additively manufactured parts for space," *In H. Helvajian, A. Piqué, and B. Gu (Eds.), Proceedings of SPIE, Laser 3D Manufacturing V*, pp. 1–14, https://doi.org/10.1117/12.2297204.

[7] Hopping, E. P., and Xu, K. G., 2017, "Design and Testing of a Hall Effect Thruster with 3D Printed Channel and Propellant Distributor," *35th International Electric Propulsion Conference 2017*; October 08-2, Atlanta, GA, United States.

[8] Borgue, O., Müller, J., Leicht, A., Panarotto, M., and Isaksson, O., 2019, "Constraint Replacement-Based Design for Additive Manufacturing of Satellite Components:

Ensuring Design Manufacturability through Tailored Test Artefacts," Aerospace, **6**(11), http://dx.doi.org/10.3390/aerospace6110124.

[9] Thomsen, B., Kokkolaras, M., Månsson, T., and Isaksson, O., 2017, "Quantitative assessment of the impact of alternative manufacturing methods on aeroengine component lifing decisions," Journal of Mechanical Design, 139(2), https://doi.org/10.1115/1.4034883.

[10] Borgovini, R., Pemberton, S., & Rossi, M., 1993, "Failure mode, effects, and criticality analysis (FMECA), RELIABILITY ANALYSIS CENTER GRIFFISS AFB NY.

[11] Seo, G., Ahsan, M. R., Lee, Y., Shin, J. H., Park, H., & Kim, D. B. (2021). A functional modeling approach for quality assurance in metal additive manufacturing. Rapid Prototyping Journal.

[12] Gibson, I., Rosen, D., Stucker, B., & Khorasani, M. (2021). Design for additive manufacturing. In Additive manufacturing technologies (pp. 555-607). Springer, Cham.

[13] Eckert, C., Isaksson, O., and Earl, C., 2019, "Design margins: a hidden issue in industry," Design Science, **5**, DOI: https://doi.org/10.1017/dsj.2019.7.

[14] Karlow Herzog, P., 2018, "Surface characterization in Additive Manufacturing-An empirical study of angular dependency," Master´s degree thesis, Lund University, ID: 8963731.

[15] Mokhtarian, H., Hamedi, A., Nagarajan, H. P., Panicker, S., Coatanéa, E., and Haapala, K., 2019, "Probabilistic Modelling of Defects in Additive Manufacturing: A Case Study in Powder Bed Fusion Technology," *Procedia CIRP*, **81**, pp. 956-961, https://doi.org/10.1016/j.procir.2019.03.234.

[16] NASA, 1970, "Qualification testing. NASA Space vehicle design criteria," NASA SP-8044. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710019569.pdf

[17] Shabi J, Y. Reich, and R. Diamant., 2017, "Planning the verification, validation, and testing process: A case study demonstrating a decision support model," Journal of Engineering Design **28**(3), pp. 171-204, https://doi.org/ 10.1080/09544828.2016.1274964

[18] ISO, 2015, "ISO/IEC/IEEE 15288:2015," Systems and software engineering — System life cycle processes. Retrieved from: https://www.iso.org/standard/63711.html

[19] Biliyard B., 2018, "Aerospace castings," NASA. NASA Marshall Space Flight Center; Huntsville, AL, United States Retrieved from: https://ntrs.nasa.gov/search.jsp?R=20170012457.

[20] Pecht, M. G., 1993, "Design for Qualification," *In Proceedings of Annual Reliability and Maintainability Symposium*, pp. 1–4, https://doi.org/ 10.1109/RAMS.1993.296885.

[21] Preussger, A., Kanert, W., and Gerling, W., 2003, "Reliability qualification of a smart power technology for high temperature application based on physics-of-failure and

risk and and opportunity assessment," *In 2003 IEEE International Reliability Physics Symposium Proceedings*, pp. 378–384, https://doi.org/10.1109/RELPHY.2003.1197777.

[22] Yadav, O. P., Singh, N., and Goel, P. S., 2006, "Reliability demonstration test planning: A three dimensional consideration," Reliability Engineering and System Safety, **91**(8), pp. 882–893, https://doi.org/10.1016/j.ress.2005.09.001.

[23] Eastman, C. M., 2012, "Design for X: concurrent engineering imperatives", Springer Science & Business Media.

[24] Seifi, M., Gorelik, M., Waller, J., Hrabe, N., Shamsaei, N., Daniewicz, S., and Lewandowski, J. J., 2017, "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification," Jom, 69(3), pp. 439–455. https://doi.org/10.1007/s11837-017-2265-2

[25] Wall, S. D. (2004, March). Model-based engineering design for space missions. In 2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No. 04TH8720) (Vol. 6, pp. 3907-3915). IEEE.

[26] Ross, T. J., 2004, "Fuzzy logic with engineering applications (Vol. 2). New York: Wiley.

[27] Zimmermann, H. J. (Ed.). (2012). Practical applications of fuzzy technologies (Vol. 6). Springer Science & Business Media.

[28] Izquierdo, S., and Izquierdo, L. R., 2017, "Mamdani fuzzy systems for modelling and simulation: A critical assessment," Journal of Artificial Societies and Social Simulation, **21**(3), https://doi.org/ 10.18564/jasss.3660.

[29] Precup, R. E., and Preitl, S., 2004, "Fuzzy Logic Decision Rules in Two Input-Single Output Linear Time-varying Systems Control," *In Proceedings of 1st Romanian-Hungarian Joint Symposium on Applied Computational Intelligence-SACI*, pp. 70-69.

[30] Hamam, A., & Georganas, N. D. (2008, October). A comparison of Mamdani and Sugeno fuzzy inference systems for evaluating the quality of experience of Hapto-Audio-Visual applications. In 2008 IEEE International Workshop on Haptic Audio visual Environments and Games (pp. 87-92). IEEE.

[31] Saridakis, K. M., and Dentsoras, A. J., 2005, "A fuzzy rule-based approach for the collaborative formation of design structure matrices," *In International Conference on Innovative Techniques and Applications of Artificial Intelligence*, Springer, London, pp. 81-94, https://doi.org/10.1007/1-84628-224-1_7.

[32] Bonjour, E., Deniaud, S., Dulmet, M., and Harmel, G., 2009, "A fuzzy method for propagating functional architecture constraints to physical architecture," Journal of mechanical design, **131**(6), https://doi.org/10.1115/1.3116253.

[33] Elkaseer, A., Mueller, T., Charles, A., and Scholz, S., 2018, "Digital detection and correction of errors in as-built parts: a step towards automated quality control of additive manufacturing," *In Proceedings of the World Congress on Micro and Nano Manufacturing (WCMNM)*, Portorož, Slovenia, pp. 18-20, https://doi.org/10.3850/978-981-11-2728-1_58.

[34] Lanzotti, A., Carbone, F., Grazioso, S., Renno, F., and Staiano, M., 2018, "A new interactive design approach for concept selection based on expert opinion," International Journal on Interactive Design and Manufacturing (IJIDeM), **12**(4), pp. 1189-1199, https://doi.org/10.1007/s12008-018-0482-8.

[35] Brice, C. A., 2011, "Unintended consequences: How qualification constrains innovation," In Proceedings of the 1st World Congress on Integrated Computational Materials Engineering (ICME), John Wiley and Sons, pp. 241, https://doi.org/10.1002/9781118147726.ch34.

[36] Diegel, O., Nordin, A., & Motte, D. (2019). A Practical Guide to Design for Additive Manufacturing. Springer Singapore.

[37] Sanaei, N., Fatemi, A., and Phan, N., 2019, "Defect characteristics and analysis of their variability in metal L-PBF additive manufacturing," Materials and Design, **182**, https://doi.org/10.1016/j.matdes.2019.108091.

[38] Yager, R.R., 2004, "Owa aggregation over a continuous interval argument with applications to decision making," Trans. Syst.Man Cyber, Part B, **34**(5), pp. 1952–1963, https://doi.org/10.1109/TSMCB.2004.831154.

[39] Johansson, C., Hicks, B., Larsson, A. C., and Bertoni, M., 2011, "Knowledge maturity as a means to support decision making during product-service systems development projects in the aerospace sector," Project Management Journal, **42**(2), pp. 32-50, https://doi.org/10.1002/pmj.20218.

[40] Kindberg, P., 2017, "Development of a miniature Gridded ion thruster", Master Thesis, Luleå University of Technology, http://urn.fi/URN:NBN:fi:aalto-201710307304.

[41] Öhrwall Rönnbäck, A. B., and Isaksson, O., 2018, "Product Development Challenges for Space Sub-System Manufacturers," *In Proceedings of the 15th International Design Conference*, pp. 1937–1944, https://doi.org/10.21278/idc.2018.0534.

[42] Villarraga-Gómez, H., Peitsch, C. M., Ramsey, A., and Smith, S. T., 2018, "The role of computed tomography in additive manufacturing," *In 2018 ASPE and euspen Summer Topical Meeting: Advancing Precision in Additive Manufacturing*, **69**, pp. 201-209.

[43] Berthold, M. R., and Hall, L. O., 2003, "Visualizing fuzzy points in parallel coordinates," IEEE Transactions on Fuzzy Systems, **11**(3), pp. 369-374, https://doi.org/ 10.1109/TFUZZ.2003.812696.

[44] Maksimovic, M., Al-Ashaab, A., Sulowski, R., & Shehab, E. (2012, December). Knowledge visualization in product development using trade-off curves. In 2012 IEEE International Conference on Industrial Engineering and Engineering Management (pp. 708-711). IEEE.

[45] Portolés, L., Jordá, O., Jordá, L., Uriondo, A., Esperon-Miguez, M., Perinpanayagam, S., 2016, "A qualification procedure to manufacture and repair aerospace parts with electron beam melting" J. Manuf. Syst. 2016, **41**,pp. 65–75, https://doi.org/ 10.1016/j.jmsy.2016.07.002.

[46] Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J. and Mistree, F. 2000. “The 'Validation Square'-Validating Design Methods. In: ASME Design Theory and Methodology Conference

[47] Sutcliffe, A., & Sawyer, P. (2013, July). Requirements elicitation: Towards the unknown unknowns. In 2013 21st IEEE International Requirements Engineering Conference (RE) (pp. 92-104). IEEE.

[48] Browning, T. R., and Eppinger, S. D., 2002, “Modeling impacts of process architecture on cost and schedule risk in product development,” IEEE transactions on engineering management, **49**(4), pp. 428-442, https://doi.org/10.1109/TEM.2002.806709.

Article F

Reducing design uncertainty through model-based collaborative design methods when introducing new technologies: A Solomon four-groups design study

Olivia Borgue [(1)], Massimo Panarotto [(1)], Ola Isaksson [(1)]

(1) Chalmers University of Technology, Chalmersplatsen 4, 412 96 Göteborg, Sweden
Olivia Borgue, borgue@chalmers.se (corresponding author)
Massimo Panarotto, Massimo.panarotto@chalmers.se
Ola Isaksson, ola.isaksson@chalmers.se

Abstract

When introducing new technologies in product design, failing to identify and address uncertainties regarding technology feasibility, and the way technology introduction impacts the whole product development process, hinder the establishment of appropriate design requirements during conceptual stages. Ill-defined design requirements often lead to unpleasant and expensive surprises that arise late on the product development process, rendering the introduction of a new technology an expensive and time-consuming endeavor.
Uncertainties about the new technology can be known (information designers know is missing), or unknown (information designers do not know is missing).
Previous research by the authors has proposed a digital design platform and respective design methods to support cooperative efforts to identify and model uncertainties during conceptual phases. In this article, the usefulness of such platform is evaluated using a Solomon Four-Groups design study featuring the design of satellite components for additive manufacturing. The results of the study suggest that the proposed digital platform and associated design methods are useful for identifying uncertainties and for proposing measures to address them, through a cooperative modeling environment.

Keywords: Digital design platform, design uncertainties, manufacturability, testability, Solomon four-groups design study.

1. Introduction

One of the most powerful strategies to ensure market permanence is the introduction of new technologies (Porter, 1985; Passemard and Kleiner, 2000).
However, new technology introduction is often hampered by uncertainties regarding technology capabilities, and the way the new technology impacts the whole product development process (Stroud, 2002). Failing to assess new technology capabilities and its impact on the oveall PDP activities, can lead to the establishment of ill-defined product design specifications and, consequently, a final product that fails to deliver the promised business benefits (Stroud, 2002; Goldberg et al., 2018).
The consequences of ill-defined design specifications can range from expensive and time-consuming redesign loops to technology abandonment (Thompson et al., 2016).
To avoid these consequences, there is a need to increase the knowledge about the new technology and reduce the number of uncertainties during conceptual phases (Dordlofva and Törlind, 2020).
In general, uncertainties can be described as known uncertainties (information designers know is missing, known unknowns, KU), or unknown uncertainties (information designers do not know is missing, unknown unknowns, UU) (Jensen et al., 2017). Strategies for dealing with known unknowns include test campaigns and assessments by experts (Sutclife and Sawyer 2013; Ramasesh and Browning, 2014; Dordlofva and Törlind, 2020). However, unknown unknowns are difficult to find as practitioners do not know what information is missing (Jensen et al., 2017), as a consequence, UU are the source of unpleasant surprises during late PDP where design changes are the most expensive. Failing to account for UU can lead to the establishment of non-adequate project budget for contingencies (Raydugin, 2012).
Previous research (REF) by the authors have proposed model-based design methods for uncertainty identification and modelling based on multidisciplinary, holistic product representations compiled in a digital design platform, and a technique of design constraints modelling and replacement.
The digital platform has been developed as a boundary object where different product representations (such as function models and activity models) can interact and support design endeavors and knowledge transfer among practitioners with different expertise and perspectives.
The proposed methods and design platform have been applied to specific case studies before, yielding positive results in the identification of uncertainties, both known and unknown; however, it is yet to be determined if the results obtained are due to the methods application or to the influence of confounding variables (Sawilowsky, 1994; Trochim, 2021).

To assess the usefulness of the proposed methods and digital design platform for uncertainty identification and modelling, an experimental set up inspired on the Solomon four-group design study was implemented to qualitatively prove or refute the following hypotheses:

Hypothesis 1: The proposed multidisciplinary, holistic design methods have a positive effect on the identification, during conceptual phases, of design uncertainties (both known and unknown) related to the feasibility of a new technology and its impact on later product development activities.

Hypothesis 2: The modelling environment supports the transformation of the identified uncertainties into known knowns.

2. Background

2.1. Uncertainties during technology introduction

Introducing new technologies in their products, companies aim at market permanence (Porter, 1985; Passemard and Kleiner, 2000).
However, not every technological change is strategically convenient, technology increases competitive advantage if it has a significant role in reducing overall costs and increasing product uniqueness or performance (Porter, 1985).
The successful assessment of a new technology introduction and the eventual establishment of design requirements for its implementation is often hampered by uncertainties (Mavris et al., 1999; Goldberg et al., 2018). These uncertainties are related to technology capabilities (what the technology is and is not capable of), and the way the technology introduction impacts the whole product development process regarding its activities, resources and schedule (Porter, 1985; Stroud, 2002; Browning and Ramasesh, 2015).
The solution to this problem is to reduce the number of uncertainties, increasing the knowledge about the new technology and its impact on the PDP (Dordlofva and Törlind, 2020). Literature (Browning and Ramasesh, 2015) divides uncertainties in two categories, known uncertainties, information designers know is missing, known unknowns (KU) and unknown uncertainties, information designers do not know is missing, unknown unknowns (UU).
Strategies for dealing with known unknowns are well-studied and implemented on literature and on industrial contexts, they often include prototyping (Elverum and Welo, 2015; Jensen et al., 2017), test campaigns or assessments by experts (Sutclife and Sawyer 2013; Ramasesh and Browning, 2014; Dordlofva and Törlind, 2020). However, unknown unknowns are difficult to find as practitioners do not know what formation is missing (Browning and Ramasesh, 2015; Jensen et al., 2017).

Moreover, UU are sometimes facts that practitioners know but did not come to their minds when designing (Ramasesh and Browning, 2014).
If the UU are left unknown, the unknown data gap about the new technologies might be filled with carried over knowledge from previous design projects, due to the tendency to design products with similar features to their predecessors (Kumke et al., 2016; Seepersad et al., 2017). As previous data is not always applicable to new design contexts, ill-defined design specifications can be established, leading to the development of products that do not fulfill their full potential (Kumke et al., 2016; Seepersad et al., 2017). Other, more serious consequences are the establishment of non-adequate project budget for contingencies (Raydugin, 2012) and the development of products that fail to deliver business benefits (Mavris et al., 1999; Goldberg et al., 2018).
Sutcliffe and Sawyer (2013) presented a review of existent techniques to deal with uncertainties. Their work indicates that techniques such as interviews, observations, workshops, scenarios, or prototypes are quite mature and well-established. These techniques can, however, be expensive or time consuming specially if they are not systematic and well-planned.
Prototyping strategies, as those proposed by Jensen et al. (2013), Borgue et al. (2019), or Dordlofva and Törlind (2020) are adequate for transforming KU into KK, however, they seldomly result on the discovery of UU. In the work by Borgue et al. (2019), for example, the authors use prototypes for shedding light into manufacturing uncertainties for additive manufacturing technologies (AM) in the context of a flow connector for satellite applications. During this process, they uncovered an UU, related to the difficulty of removing the flow connector from the building platform; for this reason, an appropriate new design specification was established to address this difficulty. Nevertheless, the discovery of this UU was accidental and relying on prototyping for UU discovery is not time or cost effective.
The work by Ramasesh and Browning (2014) and Browning and Ramasesh (2015) presents a list of factors thar foster UU, and several strategies for UU identification. On essence, techniques for UU identification call for a purposeful and systematic UU identification procedure based on modelling strategies, communication, and an alertness culture. These statements are aligned with those from Sutcliffe and Sawyer (2013), who also stated the importance of models and problem decomposition for UU identification. However, as these authors point out, there is still room for improvements in what concerns modelling strategies for UU identification.
Multidisciplinary product development modelling strategies and performance simulations are widely used for uncertainty assessment and reduction (Mavrik, 1999; Struck and Hensen, 2007; Ogaji et al., 2007; Goldberg et al., 2018) during conceptual stages. These strategies are tailored for KU reduction and for mitigating

their effect on the overall PDP, however, they are in general not concerned with the identification of UU, especially those related to design specifications. Some approaches from the software industry, such as the one proposed by Henricksen and Indulska (2004), focus on UU identification through user-based object modelling approaches to model information quality and manually flag UU. Their graphical representation is well suited for developer and user based UU identification and specification of requirements of an application. These approaches, however, are not applied to the architecture design of hardware.

In general, there is a lack of systematic model-based (Sutcliffe and Sawyer, 2013; Browning and Ramasesh, 2015; Dordlofva and Törlind, 2020) platforms to systematically identify, model and solve design specifications uncertainties.

2.2. A multidisciplinary design platform to model uncertainty and identify unknown unknowns

Previous work by the authors (REF) have proposed the implementation of a multidisciplinary digital design platform for identifying, modelling, and solving design specifications uncertainties through the collaborative efforts of practitioners with different expertise.

This digital design platform is based on product architecture representations realized on enhanced function models (FM). This platform is intended to act as a boundary or intermediary object (Boujut and Blanco, 2003) to foster collaboration among practitioners with different expertise and support design exploration and decision making.

The function models the platform is based on, present a hierarchical decomposition of a product architecture from the main product functional requirement (FR) to the lowest level FRs to ensure product performance (Claesson, 2006). One design solution (DS) is assigned to each FR, representing the function´s physical embodiment in the product architecture (Figure 1). Moreover, constraints are linked to the DSs, to reduce design space and specify the boundaries inside which the DS should be realized. In the case of new technology introduction, and in this model representation, constraints are related to technology capabilities and testing in the context of the PDP.

To evaluate the impact that different product architectures have on the PDP, the platform links the function model (FM) with PERT diagrams that model the different PDP activities. Moreover, to enable schedule assessment and optimization, the risk of not performing a certain activity (or performing it partially) is included on PERT diagram and on the portion of the FM related to that activity.

In Figure 1, the FM in which the product architecture model is based on is presented along the respective PERT diagram. An example featuring a flow connector for satellite applications and its respective validation activities is included in the Figure

1 as well, to illustrate the connection of the FM with the activity models and risk assessment.

To identify UU related with new technology introduction, a process of constraints replacement is proposed. As design processes rarely start from scratch, many design and development processes with new technologies start from an old product that implements a previous, well-established technology. In the process of constraints replacement, the FM of the product with the previous technology is reused, and the constraints related to the old technology are removed and replaced with their counterparts for the new technology.

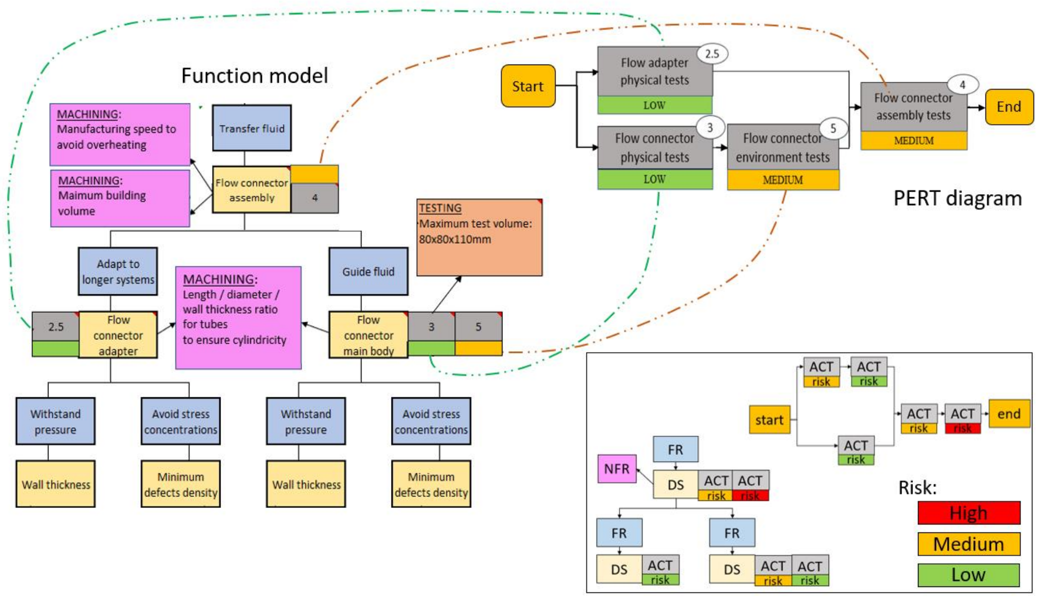


Figure 1. Proposed design platform that links a product´s function model with PERT diagrams and risk assessments about downstream PDP activities.

In the example from Figure 1 the flow connector is traditionally machined from a metal block, and the constraints in the function model are related to this manufacturing technology. To redesign the flow connector for, for example, additive manufacturing, the machining constraints are removed and replaced with their AM counterparts, as presented in Figure 2.

Through this constraints replacement technique practitioners are encouraged to systematically analyze how a new technology would affect a product architecture and PDP activities. This way, new technology KU can be included in the architecture analysis during conceptual phases. Moreover, the constraints replacement procedure enables the discovery of UU related to technology feasibility and the effect the technology has on the PDP.

The constraints replacement technique and the design platform have been applied to specific case studies before, yielding positive results in the identification of design specifications uncertainties; however, it is yet to be determined if the results obtained are due to the methods application or to the influence of confounding variables (Sawilowsky, 1994; Trochim, 2021).

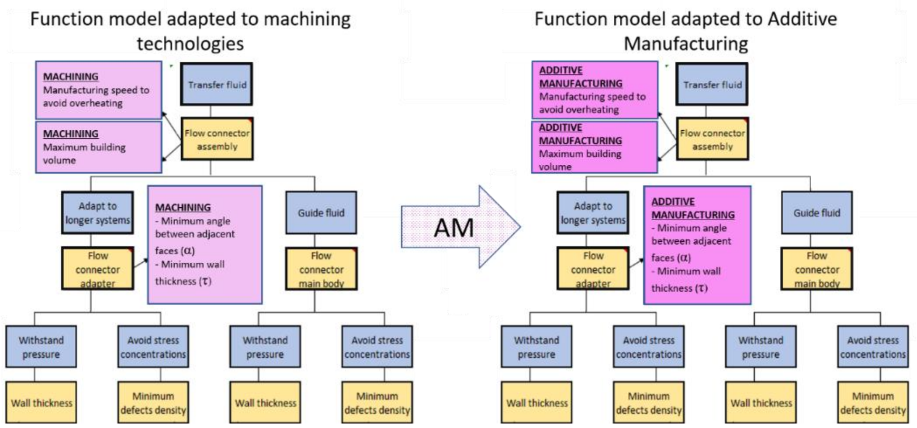


Figure 2, constraints replacement procedure.

2.3. Experimental design methods for evaluating the usefulness of a method

One of the simplest methods for evaluating the usefulness of a method or a tool is a two-group posttest-experiment (Figure 3.a) (Trochim, 2021). In this arrangement, one group applies the method or tool to perform a task, and the other group does not. The results are them compared based on preestablished metrics. However, this method does not provide a way to compare both groups' baselines, so the results from these studies could be due to intrinsic differences between the two groups. For instance, when evaluating the usefulness of a design tool for reducing conceptual design times, the two groups could represent two different companies. If one company uses the tool and the other does not, it is not possible to know if the differences obtained in design times are due to the tool or the companies.
One way to establish a baseline to compare both groups is performing a pretest-posttest experiment (Figure 3.b) (Trochim, 2021). In this arrangement, both groups perform a pretest, to establish their baseline results to be then compared with the results obtained after applying the method or tool of interest. When evaluating the design times of two companies, a pretest would establish a comparison of the current (without the tool) design times of each company.
Nevertheless, a drawback of this configuration is the difficulty to establish if the obtained results are due to the method, or the "practice" obtained during the pretest. The Solomon Four-Group Design (Figure 3.c) (Sawilowsky, 1994; Trochim, 2021) is an experiment arrangement designed to deal with the effects of the pretest. This arrangement requires four groups, two of the groups use the method or tool and two do not. Furthermore, two of the groups receive a pretest and two, do not.

This experiment design is more complex to set up and analyze due to the number of groups involved, however, it reduces the internal validity issues, enables the researcher to exert better control over the experiment variables, and to make sure that the pretest did not influence the experiment results (Sawilowsky, 1994; Trochim, 2021; May et al., 2020).

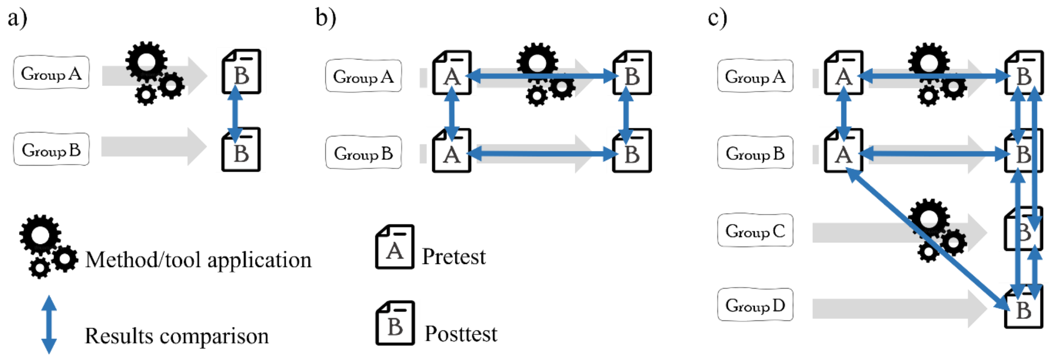


Figure 3. Comparison of experimental design methods

3. Method

To evaluate the previously proposed holistic design platform and the technique of constraint replacement, the Solomon-four group design experiment was implemented in the context of a Swedish research project.

This project aimed at demonstrating the development of a digital infrastructure and platform for the industrialization of Additive Manufacturing (AM). Industrial case representatives, digital environment providers and research institutes were brought together as representative stakeholders to the introduction of AM in industrial contexts. The objective of the project was to evaluate current solutions enabling digital data traceability and digital modelling and simulation activities for optimal design of product and process definition.

In this research project, the proposed design platform served two objectives: (1) Evaluate the platform´s usefulness to identify UU and propose measures to cope with them; (2) Showcase design capabilities developed through four years of previous research.

To evaluate the platform´s usefulness, the Solomon-four group design experiment was preferred, as it has been proved advantageous to reduce the effect that confounding variables and external factors have on the study results (Trochim, 2021).

A purposeful, homogeneous sampling (Palinkas et al., 2015) with two associative hypotheses in a qualitative study context (Chigbu, 2019), was preferred.

A total of 12 industrial practitioners participated in the study in six groups of two participants. Moreover, a test run was performed at the beginning of the study with two extra participants to adjust experiment details and improve instructions. Further details of the experiment and its participants are found in the next section.

The Solomon-four group design experiment showcased the design platform to industrial practitioners as well. Moreover, after the study was finished, its results were presented to the research project participants, which enabled a further discussion, included in the "Results" section of this article.

3.1. Solomon-four group design experiment

The experiment was designed to probe or refute two hypotheses:

Hypothesis 1: The proposed multidisciplinary, holistic design methods have a positive effect on the identification, during conceptual phases, of manufacturability and testability unknown unknowns related to the implementation of a new technology.

Hypothesis 2: The proposed multidisciplinary, holistic design methods have a positive effect on the establishment of measures to address the identified uncertainties.

In this experiment, two design case studies are implemented where practitioners evaluate the redesign for AM of two products which are part of a fluid management system of a satellite: (1) a flow connector and, (2) a heat exchanger.

To limit the scope of the study, the function models of the analyzed products contained only constraints related to manufacturability and testability. Moreover, the PERT diagrams used in the study have just included the system´s validation activities, which in the context of space components are comparable with the qualification or acceptance phases. Validation activities are those performed to control if the product fulfills the intended function and business case.

The Solomon-four group design experiment was performed twice (Iteration 1 and Iteration 2), each time with three groups of two participants each. On the first iteration, the flow connector was used the pre-test, and the heat exchanger as the test. On the second iteration, the roles were inverted, and the heat exchanger was used as the pre-test and the flow connector as the test. This way, the need for Group D was eliminated, as its results are obtained from the Group A of the opposite iteration (Figure 4). Moreover, interchanging the pre-test and test increases results reliability, as it eliminates the concerns of the methods results being due to the test of choice.

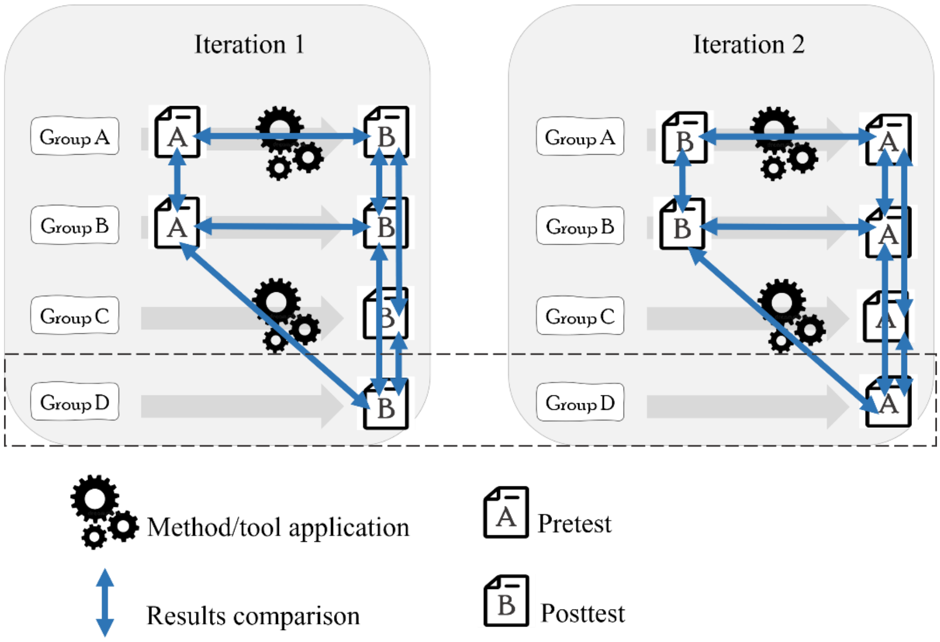


Figure 4. Implemented Solomon-Four Groups experiment design.

Table 1. Experiment participants´ company roles and experience (ys)*

	Group	Participant	Current company role	Total industrial experience	Total experience working with AM	Experience in professional roles as a designer	DfAM professional experience	Experience in professional roles involving test planning or test performance
Iteration 1	A	1A1	Business analyst	4	1	0	0	0
		1A2	CEO	5	8 months	6 months	6 months	3 months
	B	1B1	AM Research engineer	13	3.5	6 months	1.5	0
		1B2	Lead product developer	6	6	-	-	6
	C	1C1	Engineer lead for AM	3	2	0	2	0
		1C2	Software Engineer	4	4	0	0	0
Iteration 2	A	2A1	R&D engineer	+20	2.5	+20	2.5	+15
		2A2	Researcher in data science	8	3	0	0	0
	B	2B1	R&D engineer	27	3	0	3	0
		2B2	Technical project leader	15	6	3	3	3
	C	2C1	Researcher	3.5	3.5	0	3	7
		2C2	Technical product responsible	24	3	24	3	0

*Experience is expressed in years unless explicitly expressed in months

3.2. Case studies for pre-tests and tests

The two products implemented in the experiments are part of a fluid management system of a satellite. A branch of a fluid management system is made of seven components, schematized in Figure 5: (1) Heat exchanger, (2) Pressure sensor, (3) Temperature sensor, (4-6) Pressure vessel A, B and C, (7) Flow connector.
The flow connector and the heat exchanger were redesigned for AM, the experiment participants were presented with the task of analyzing those redesigns (weather during a pre-test or a test) and voice their concerns related to component manufacturability and testability. The concerns that practitioners mention are interpreted as uncertainties.

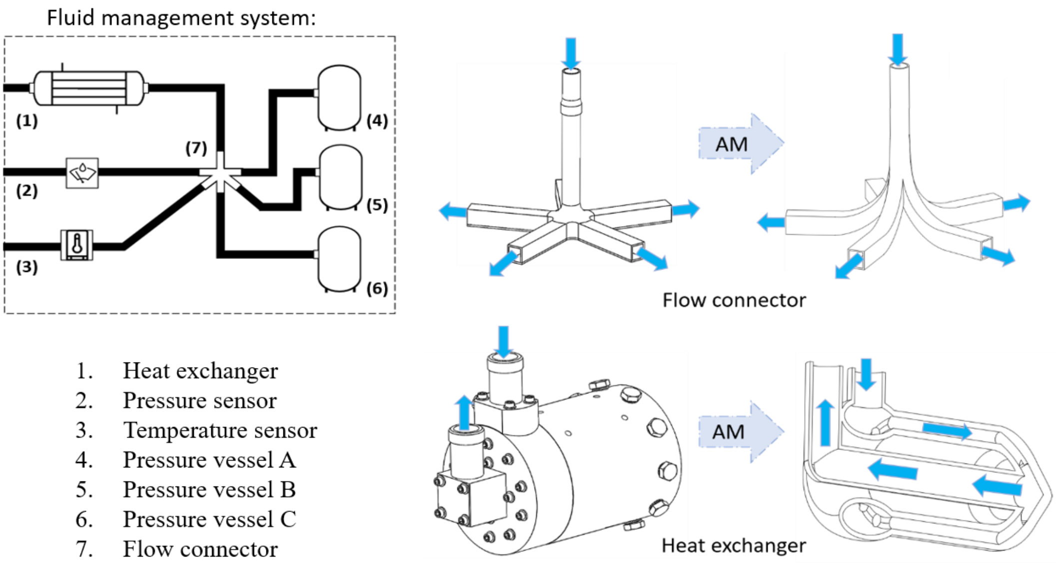


Figure 5. Conventionally manufactured (left) and redesigned for AM (right) flow connector and heat exchanger.

3.3. Activities performed during the experiments

The experiment was performed twice, iteration 1 (I1) and iteration 2 (I2), with six participants in each iteration, divided in three groups, Group A, Group B and Group C. A series of activities, presented in Table 2, were performed for the different groups, respecting the stipulated activity durations and sequence.

Table 2. Activities performed at the Solomon-Four Group experiments

Activity	Length (min)	Description	Group A	Group B	Group C

Introduction	20	AM capabilities variation across AM technologies, machines, and geometries. Introduction to the experiment´s tasks.	Introduction to document 1, pre-test and test tasks, and design platform.	Introduction to document 1 and pre-test and test tasks.	Introduction to document 1 and test tasks.
Read Tasks documentation	5 – 8	Participants read the experiment´s documentation on their own. They have 5 minutes that can be extended to 8 if they needed (in case of language difficulties, for example).	Read documents 1, 2 and 3	Read documents 1, 2 and 3	Read documents 1, and 3
Pre-test	20	Participants are presented with the pre-test redesign assessment activity, where they are tasked with voicing their concerns about the manufacturability and test ability of the product redesigned for AM.	Flow connector or heat exchanger (depending on iteration)	Flow connector or heat exchanger (depending on iteration)	-
Introduction to test	5	Transition between pre-test tasks and test tasks. Participants are given 5 minutes to read the documentation for the test	Read document 3, about the flow connector or heat exchanger (depending on iteration)	Read document 3, about the flow connector or heat exchanger (depending on iteration)	-
Digital platform presentation	10	Participants are introduced the digital design platform. On the platform, both the flow connector and the heat exchanger are already modelled and connected with the test activities PERT diagram.	Emphasis on the models of the product used for the test	Emphasis on the models of the product used for the test	Emphasis on the models of the product used for the test
Test	20	Participants are presented with the test	Heat exchanger	Heat exchanger	Heat exchanger

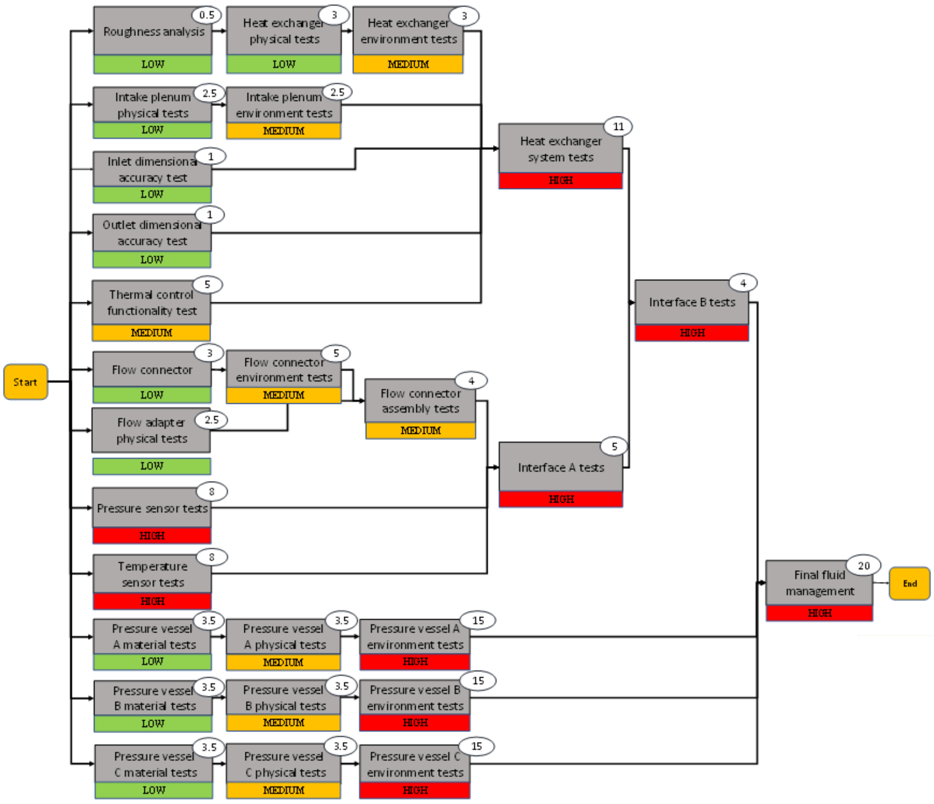
		redesign assessment activity, where they are tasked with using the digital design platform for voicing their concerns about the manufacturability and test ability of the product redesigned for AM.	or flow connector (depending on iteration)	or flow connector (depending on iteration)	or flow connector (depending on iteration)

Three different documents are handled to groups A and B:

- Document 1, AM capabilities and limitations: The experiments are based on metal laser powder bed fusion (LPBF) AM technologies; this document summarizes what can and cannot be manufactured with these technologies. Among others, minimum manufacturable wall thickness or threshold surface angle for requiring supports structures.
- Document 2, pre-test documentation: The conventional geometry, materials, dimensions, and manufacturing processes of the product used for the pre-test; a table with the required product validation activities, the elements required for each activity, the activity duration, and the risk of not performing the activity; a PERT diagram displaying the validation activities sequence in the context of the whole fluid management system; the product redesigned for AM. Depending on the experiment iteration, document 2 can be about the flow connector (Iteration 1) or the heat exchanger (Iteration 2).
- Document 3, test documentation: The conventional geometry, materials, dimensions, and manufacturing processes of the product used for the test; a table with the required product validation activities, the elements required for each activity, the activity duration, and the risk of not performing the activity; a PERT diagram displaying the validation activities sequence in the context of the whole fluid management system; the product redesigned for AM. Depending on the experiment iteration, document 2 can be about the flow connector (Iteration 2) or the heat exchanger (Iteration 1)

Groups C received only documents 1 and 3, as they do not have a pre-test.

The purpose of the documentation is to mimic real design processes and the information that is collected and available at conceptual stages. In Figure 6, an extract of the PERT diagram (6.a) and validation activities table (6.b) are presented.



a)

Component	Activity	Comments	Duration (days)	Risk*
Heat exchanger channels	**Physical tests**			
	Dimensional accuracy	Xradia 610 & 620 Versa. 120x120x120mm chamber.	1.5	LOW
	Defects density		1.5	LOW
	Roughness analysis	Roughness Tester PCE-RT-11	1	LOW
	Harsh environment test			
	Leak testing	Sentinel Blackbelt Pro	1	MEDIUM
	Vibration	ASLI Electrodynamic vibration systems	1	MEDIUM
	Vacuum	Sentinel Blackbelt Pro	0.5	MEDIUM
Intake plenum	**Physical testing**			
	Dimensional accuracy	Xradia 610 & 620 Versa. 120x120x1220mm chamber.	1	LOW
	Defects density		1.5	LOW
	Harsh environment tests			
	Leak testing	Sentinel Blackbelt Pro	1	MEDIUM
	Vibration	ASLI Electrodynamic vibration systems	1	MEDIUM
	Vacuum	Sentinel Blackbelt Pro	0.5	MEDIUM
Heat exchanger inlet	Dimensional accuracy	Matter and Form 3D Scanner V2	1	MEDIUM
Heat exchanger outlet	Dimensional accuracy	Matter and Form 3D Scanner V2	1	MEDIUM
Thermal control system	Thermal cycling	ASLI Temperature cycling test chamber	5	MEDIUM
Heat exchanger system	**Harsh environments tests**			
	Pressure aging test	HAST Accelerated Aging Test Chamber	2	HIGH
	Thermal efficiency		2	HIGH
	Leak testing	Sentinel Blackbelt Pro	2	HIGH
	Vibration	ASLI Electrodynamic vibration systems	2	HIGH
	Vacuum	Sentinel Blackbelt Pro	2	HIGH

b)

Figure 6. Extract of the validation activities table and the PERT diagram.

3.4. Variables of interest

During the study, participants are asked to voice their concerns related to:

(1) design manufacturability (weather physical features in the product are manufacturable with LPBF technologies or not).

(2) manufacturing processes (process parameters, manufacturing speed, manufacturing costs, post processing activities, “hybrid manufacturing”).

(3) test ability (ability to test the product or its physical features, how the AM design would affect test schedules in terms of duration and costs) (Valfre, 2012).

These concerns are “matters that cause feelings of unease, uncertainty, or apprehension” (MerriamWebster, 2021) to practitioners about technology capabilities (what can and cannot be achieved with AM) and the respective VVT activities.

What is measured in the experiments is the number of concerns (uncertainties) and the number of proposed design changes:

- Number of concerns about manufacturability (Nm): weather physical features in the product are manufacturable or not.
- Number of concerns about manufacturing processes (Nmp): process parameters, manufacturing speed, manufacturing costs, post processing activities, “hybrid manufacturing.
- Number of concerns about test ability (Nt): ability to test the product or its physical features, how the AM design would affect test schedules in terms of duration and costs.
- Number of proposed measures to address design manufacturing concerns, includes manufacturability and manufacturing processes (NMm).
- Number of proposed measures to address test concerns (NMt).

The success criteria (Blessing et al., 1998) utilized to probe H1 and H2 are a higher number of concerns and proposed measures observed with the use of the design platform than without it.

4. Results

In Table 3 the measured variables from the experiment are presented, categorized according to group and experiment iteration. The specification “Method” or “No method” refers to the use or not of the proposed design platform and constraints replacement procedure.

In Table 4, the differences between the two case studies, flow connector and heat exchanger, are presented. In Table 4, the influence of the pre-tests is also highlighted, as the results are categorized as “No practice” (no pre-test) or “With practice” (with pre-test).

Table 3. Measured variables from the Solomon Four-Groups experiments.

Iteration	Group		Nm	Nmp	Nt	NMm	NMt	Risk mentioned in the discussion
1	A	Pretest – No method	4	0	1	0	1	No
		Test - Method	7	1	2	0	5	Yes
	B	Pretest – No method	6	4	0	6	1	No
		Test – No method	5	1	2	1	4	No
	C	Pretest	-	-	-	-	-	-
		Test - Method	9	8	5	2	3	Yes
2	A	Pretest – No method	4	1	0	2	2	Yes
		Test - Method	9	4	1	1	4	Yes
	B	Pretest – No method	4	3	1	3	0	No
		Test – No method	3	1	0	2	0	No
	C	Pretest	-	-	-	-	-	-
		Test - Method	10	6	3	6	6	Yes

From Tables 3 and 4, four results can be obtained:

- The measured variables do not depend on the case study, the flow connector and the heat exchanger obtained similar results for every variable.
- The pre-test activities do not seem to have a positive impact on the test results. Moreover, in the pre-test seems to have a negative effect on the amount of the number of concerns identified and the number of proposed measures to address uncertainties.
- For both case studies, the number of concerns identified and the number of proposed measures to deal with uncertainty increased with the use of the design platform.
- In every instance where the design platform was implemented practitioners held discussions about activity risk and used the provided risk assessments to propose measures to deal with test and manufacturing uncertainties. Only one group (It2 GA) included risk in their discussions without the support from the design platform.

Table 4. Comparison of flow connector and heat exchanger case studies

		Flow connector		Heat exchanger	
		No method	Method	No method	Method
Nm	No Practice	4	10	4	9
		6	-	4	-
	With Practice	3	9	5	7
Nmp	No Practice	0	6	1	8
		1	-	3	-
	With Practice	1	4	1	1
Nt	No Practice	1	3	0	5
		2	-	1	-
	With Practice	0	1	2	2
NMm	No Practice	0	5	2	2
		0	-	3	-
	With Practice	2	1	1	0
NMt	No Practice	1	6	2	3
		5	-	0	-
	Practice	0	4	4	5

In Table 5, the identified manufacturing and test concerns and measures are presented in relation to the group that identified them. Concerns explicitly included in the design platform as concerns for machining technologies are highlighted with an asterisk (*).

Table 5. Identified manufacturing and test concerns and measures are presented in relation to the group that identified them.

	Iteration 1					Iteration 2				
	A		B		C	A		B		C
Manufacturing concern	FC	HE	FC	HE	HE	HE	FC	HE	FC	FC
Max. manufacturing volume *		x			x		x			x
Min. manufacturable radius *		x					x			x
Min. manufacturable hole diameter*					x		x			x
Geometry changes between adjacent sections			x							x
Threshold angle for support structures	x	x	x	x			x	x		x
Max. diameter for horizontal holes without support			x		x					
Part geometry to enable removal of support			x							
Max. manufacturable aspect ratio *		x			x		x			x
Min. manufacturable wall thickness *	x	x	x		x		x	x	x	x

Max. length, diameter, wall thickness ratio *		x	x		x		x			
Min. achievable surface roughness *	x	x		x			x			x
Surface quality improvement			x							
Max. manufacturing speed to avoid overheating *		x			x		x			x
Process parameters to avoid deformations			x							x
Dimensional accuracy	x						x	x	x	
Recoating blade problems (blade crush)			x					x		
Part removal from building plate			x							
Influence of manufacturing orientation				x	x	x	x	x	x	x
Anker the part to the building plate				x						
Min. feature size to enable removal of powder				x		x				
Mechanical properties homogeneity					x					x
Min. feature size dependency on the material					x					
Influence of layer thickness					x					
Influence of idle time between layers					x					
Influence of manufacturing atmosphere					x					
Influence of manufacturing temperatures					x					
Influence of number of lasers					x					
Number of parts on the building plate					x		x			
Influence of location on the building plate					x	x				
Wall thickness separation between internal channels						x				
Hybrid manufacturing (machining + AM)						x		x	x	
Defects generation and overheating depending on material										x
Defects generation depending on manufacturing parameters										x
Test concerns										
Influence of design on the test schedule	x									
Fit in the test chamber *		x					x			x
Cost of changing a test		x								
Inspection of internal geometries				x						
CT scan penetration depth				x	x					
Component criticality					x					
Need for stress relief before plate removal					x					
Test of variable mechanical properties					x					
CT scan resolution					x					
Influence of material on CT usefulness										x
Affordability of CT scans										x

Ultrasonic testing										x
Measures to address manuf. concerns		b			b		b			b
Change holes geometry			x			x		x	x	x
Make bottom self-supporting			x							
Smooth sharp corners			x					x		x
Integrate smart fixtures			x	x				x		
Make angles between channels larger than 90						x				
Separate inlet from outlet						x				
Separate in several components									x	
Downscale the component							x			x
Increase wall thickness										x
Increase scanning time										x
Increase layer thickness										x
Measures to address test concerns										
Perform a mock-up test schedule	x									
Change a test		x	x		x		x			x
Change the design		x								x
Downscale the component										x
Remove a test		x				x	x			
Accept a longer test schedule		x								
Change the schedule (test order)										x
Gather further information for test removal		x								
Introduce a new test			x	x			x			
Consult CT expert				x						
Perform serial testing				x						
Reduce testing by improving process monitoring				x	x					
Ensure process repeatability					x					
Test a couple of representative samples					x		x			x
Test several components at the same time for distributing the test activities and shortening the schedule										x

(*) Concerns explicitly included in the design platform as concerns for machining technologies.

4.1. Qualitative assessments from participants

During the experiments, practitioners were asked to provide feedback from the digital platform and the design experience from the experiments. Moreover, after the study was finished, the results were compiled and presented to the practitioners on the research project to open a discussion about design support platforms and uncertainty identification.

Practitioners agreed on the fact that without the digital platform, it is difficult to understand and analyze the influence that design changes (in this case, from the introduction of AM) have on the test schedule.

This problem seems to be present in regular design scenarios, as practitioners mentioned '(AM) Sales pitches are about complexity for free and constraints reduction, but (the cost of testing) is not as frequently mentioned' and 'the platform puts a finger in a place we currently do not focus a lot, which is testing and validation and how we can change the validation phases'. Linking the test activities with the architecture model allows designers to include testing on the early design trade-off analysis and make design choices that will reduce the cost and duration of the test phases.

The FM-PERT connection has also highlighted some concerns that need to be addressed for an effective introduction of AM in industrial contexts. For critical components, validation is of extreme importance, however, due to the physical phenomena that takes place during AM processes, the validation activities of AM components become too expensive and time consuming. To reduce costs and foster AM industrialization, the focus must be set on ensuring manufacturing repeatability and validation. To smoothen the transition between current AM capabilities and fully repeatable AM processes, practitioners proposed improving the design platform with AI technologies:

> 'The platform can be combined with AI technologies to feed the model with the likelihood of build success, it could be used to reduce risk. Which would be something that evolves and improves over time. So, you start with very high validation costs and over time (when the AI gains experience on manufacturing assessment) you reduce costs with AI'.

The reason why the digital design platform enables the inclusion of test phases during design decision making on conceptual stages is its visualization capability. Most of the practitioners mentioned that the platform helped them visualize product architecture and its influence on test activities '(the design platform) helps with visualization and (design) choices'. Moreover, the level of detail is appreciated, as it does not group too many things together which enables the platform evolution to fit new data and companies´ specific needs. The level of detail and the FM-PERT connection enables performing a sort of SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, 'You can find opportunities to redesign quite early, you reduce reprinting processes (and costs) and redesign loops'. Overall, the design platform can serve to indicate where extra printing simulations (to gather missing data) might be necessary, instead of printing directly and risking the rework associated with failed manufacturing, 'The connection with the PERT diagram is useful for experienced designers, they can easily see where the weaknesses and threats in the design are. Where do I need to focus? Where do I need to put more (simulation or test) resources?'.

The inclusion of the risk of not performing a test activity was appreciated, especially in the context of products where validation activities are traditionally time consuming and expensive, as is the case for the space industry. The benefit of including this risk on the FM and PERT diagrams is related with the possibility of considering not performing a test, if the risk of not performing this test is sufficiently low, and its implications on cost reduction 'If you think about the component industry and all the quality assurance procedures that you can actually shave off your process…it will save you a lot of money immediately' . However, strong arguments are required to remove test activities and the design platform is not enough to make this type of decisions. Instead, it can point designers to open a conversation about this possibility and to gather the necessary data to make such decision '(The platform) is good to start a conversation about risk management and risk reduction. Maybe we can reduce the risk of some tests but we have to increase the part costs'.

In general, de design platform was recognized as a useful boundary object to foster communication among design teams and experts from different areas.

Practitioners indicated some of the design platform weaknesses as well.

On the current version, the platform does not include pictures of the product, which hinders the manufacturability assessment, especially for unexperienced practitioners.

Regarding the constraints replacement procedure, some practitioners indicated that is a practice that would benefit unexperienced practitioners mostly 'The constraints replacement technique is mostly unnecessary for experienced practitioners'. Unexperienced designers can systematically go through the constraints for the previous implemented technology (in the case of the study, machining) and try finding their counterpart for AM. Through this procedure, they can find AM uncertainties previously unknown and learn about AM at the same time.

However, other practitioners indicated that that the design platform also benefits experienced designers as it guides their discussion (*'It points you out in the right direction'*) and acts as a conversation starter, that fosters reflection and knowledge echange. These statements are supported by the authors´ observations during the experiments.

Moreover, it was also observed that the design platform served as a knowledge transfer tool from experienced practitioners to unexperienced practitioners ('I learned a lot today!').

It was also suggested that more time was required to fully understand the design platform and make use of its full potential. Moreover, it was stated that the results using the platform might improve over time as designers gain experience and the platform is enhanced with new data ‘The more you use it, the better it gets. Is easy to adapt because the model is detailed’ .

In general, practitioners manifested that they were interested in trying the platform for their daily design activities.

5. Discussion

The usefulness of a digital design platform for supporting design uncertainty identification and mitigation, was evaluated through a Solomon Four Groups experiment design. Its usefulness was evaluated according to H1, useful for uncertainty identification and modelling, and H2, useful for transforming uncertainties into certainties.

The results suggest that the design platform enabled discussions about activity risk, and its use to propose measures to deal with uncertainties without compromising product quality while maintaining an affordable validation schedule. For example, the platform enables the identification of test activities with low risk and that can be removed or replaced with an inexpensive alternative.

However, strong arguments are required to remove test activities and the design platform is not enough to make this type of decisions. Instead, it can point designers to open a conversation about this possibility and to gather the necessary data or acquire the expertise to make such decision.

It was observed that implementing the design platform, the number of manufacturing and test concerns identified (uncertainties) and the number of proposed measures to deal with those uncertainties increased with the use of the design platform.

As the number of identified concerns increased with the implementation of the constraints replacement process, it can be concluded that this process is useful for identifying UU. Moreover, certain concerns were only identified through the constraints replacement method, such as “*Max. manufacturing volume*”, “*Max. manufacturing speed to avoid overheating*”, “*Max. aspect ratio*”, or “*Fit in the test chamber*”.

However, a drawback from this technique is that UU, are discovered if their traditional technology counterpart is well modelled. In this sense, the usefulness of this process is related with the model´s depth, breadth, and fidelity (Haskins et al., 2015). The concerns “*Min. feature size to enable removal of powder*” and “*Part geometry to enable removal of support structures*” for example, are well-known AM concerns, however, they do not have a direct machining counterpart and were not mentioned by any group using the design platform.

These results resonate well with the work by. Roth et al. (2010) which state that the performance of past designs does not address all the sources of design uncertainty related with the introduction of new technologies. The main problem in this case is that not every constraint of a new technology can be found in a traditional technology counterpart. However, the design platform and the constraints replacement method itself serve as conversation openers, to initiate a discussion about technology uncertainties, and to promote knowledge exchange among practitioners within different disciplines. As proposed by Browning and Ramasesh (2015), an organization that is actively looking for UU is more likely to identify them and turn them into KU.

It was also observed during the experiments that many uncovered UU were not really UU, but aspects of the design, manufacturing process or testing that scaped the mind of the participants at the moment of the experiment. For instance, the concern "*Max. manufacturing volume*" is one of the more evident AM limitations, however, this concern was only mentioned by participants using the design platform and constraints replacement method. This observation was in line with literature (Ramasesh and Browning, 2014), in real design scenarios, UU are sometimes things that spaced the mind of practitioners or things that no one has bothered to find out. Moreover, they propose two types of UU, the knowable UU and the unknowable UU. The constraints replacement technique addresses the knowable UU.

Regarding UUs, there is a connection between the practitioners´ expertise and the number of UU they are able to identify with or without the design platform.

In group C from Iteration 1, one of the participants has 2 years of experience working exclusively with AM and design for AM, which enriched the discussion in this group. This group identified 17 manufacturing and manufacturing processes concerns, from the discussions enabled by the process of constraints replacement.

On the contrary, the participants of Group A from Iteration 1 where not that experienced in AM. Through the process of constraints replacement, this group identified eight manufacturing and manufacturing parameters concerns, seven of which were almost identical to their machining counterpart.

Workshops participants had different experience levels, and uncertainties that are unknown for a practitioner might be known for another. The design platform made explicit the knowledge of experienced practitioners, facilitating knowledge transfer to the less experienced.

The design platform and constraints replacement procedure support unexperienced designers, that otherwise, would not be able to identify as many uncertainties. Furthermore, for unexperienced practitioners the design platform serves as a training tool as well, as it was recognized as an efficient way to acquire and store information.

Furthermore, the platform´s customizable depth, breadth, and fidelity, allows for the adaptability and flexibility required when changes such as new technologies, new organizational processes or change of market focus, occur (Subrahmanianet al., 2003).

The results from the experiments suggest that while the platform supports uncertainty identification and modeling, it also supports the process of proposing affordable measures to deal with the uncertainties. While several measures to deal with uncertainty are experience dependent, the link between the FM and the PERT diagram highlights design and validation schedule changes that could reduce uncertainty or mitigate their effects in a cost and time efficient manner. For instance, only participants that did not use the platform proposed *"Perform serial testing"* as a measure to reduce uncertainties, however, this measure is time and resource intensive and can render a project unaffordable (Brice, 2011). Participants using the design platform had the possibility of simulating and observing the effect that these types of measures would have on the overall schedule affordability. Moreover, only participants using the platform proposed *"Focus on process repeatability*" to reduce the need for test activities performed on the product.

However, the platform is not intended to replace other design and uncertainty identification methods, rather, is intended to complement them. For example, practitioners stated that the platform would work better if it was connected to a CAD (physical) product representation that enables the analysis of a product´s geometry. These statements are in line with the work by authors such as McKoy et al. (2001) who sustain that graphical product representations are better than textual representations for engineering design idea generation processes.

Moreover, other techniques for UU identification, such as interviews, observations, workshops, scenarios, or prototypes (Sutcliffe and Sawyer, 2013), should not be left aside. They should be performed before or in parallel with the implementation of the design platform and complement its information. Designers should strive for a communication, and an alertness design culture that fosters the purposeful and systematic identification of UU (Ramasesh and Browning, 2014; Browning and Ramasesh, 2015).

The proposed design platform and other UU identification methods are a powerful complement for the multidisciplinary product development modelling strategies and performance simulations (Mavrik, 1999; Struck and Hensen, 2007; Ogaji et al., 2007; Goldberg et al., 2018) currently implemented for uncertainty assessment and reduction during conceptual stages.

In general, implementing the design platform, the number of uncertainties and proposed measures to deal with those uncertainties increased. However, the sample size of this study (which is its most relevant limitation) is too small and the obtained results cannot be generalized (Yin, 2003). Moreover, due to time and resources constrains, getting a randomized pool of experienced industrial practitioners able to participate in a one-and-a-half-hour experiment is very unlikely. In this situation, a non-random group of practitioners (from the available research project) and a non-random assignment of to the groups was necessary, this choice undermines the strength of the experiment as well.

Another limitation of this study is the artificial design setting. Practitioners from different companies were paired according to their availability and their previous experience with design and AM. In addition, one of the authors of this study was present during the experiments guiding the design analysis activities, which have likely impacted the results.

Moreover, experiment participants were unfamiliar with the type of product proposed for the case studies, as well as with each other. Team and case study familiarity is possibly another confounding variable in the study, research shows that the performance increases when team members are familiar with each other and trust each other (Arrow et al. 2000; Hargadon and Bechky, 2006).

Adding to the design setting artificial nature, the design intervals were restricted to 20 minutes each. On one side, some sessions needed to be cut short, it is possible that additional uncertainties and related mitigation measures would have been mentioned. On the other side, some other groups needed to "be forced" to talk during the 20 minutes, possibly due to the discomfort generated by a lack of perceived expertise on the unfamiliar case studies and a lack of familiarity with the design partner. Another consequence of the time-constrained design set up is that the pre-test seems to have a negative effect on the amount of the number of concerns identified and the number of proposed measures to address uncertainties during the test. One possible explanation that the authors find for this phenomenon is that the pre-test and test case studies we designed to foster the identification of similar concerns, to enable case study comparison. However, as both pre-test and test were performed within the same hour, having similar uncertainties, it is possible that some uncertainties that were mentioned on the pre-test were not mentioned on the test as an unconscious attempt to avoid redundancy.

It is evident that the artificial design setting affected the study results, however, literature shows that a large proportion of the research experiments performed for testing new tools and design methods are conducted in artificial settings and their results are still useful for industry and academia (Ellis and Dix, 2006).

Despite this study not presenting statistically relevant results, it was useful as a discussion enables about design support platforms and a culture of uncertainty seeking. Moreover, the results of this study were used to obtain further funding that will enable the development of an improved version of the digital design platform that can be implemented in real industrial settings for further research purposes.

6. Conclusion

When introducing new technologies in product design, design uncertainties hinder the establishment of requirements during conceptual stages. Ill-defined design requirements can lead to expensive and time-consuming redesign loops.

Uncertainties can be known (information designers know is missing), or unknown (information designers do not know is missing). Unknown uncertainties present a big threat to a product development budget and schedule, as they are difficult to identify especially during early design phases.

In this article a digital design platform and a technique of constraints replacement are evaluated regarding their usefulness to identify new-technologies-related unknown uncertainties and measures to deal with them.

The platform and method are evaluated with a Solomon Four-Groups design study involving 12 experienced industrial practitioners and featuring the design of satellite components for additive manufacturing. The results of the study suggest that the proposed platform and associated design methods are useful for identifying uncertainties and for proposing measures to address them. Moreover, it servs as a conversation starter, to initiate discussions about technology uncertainties, fostering collaboration and knowledge transfer among practitioners with different expertise and from different disciplines. The results further highlight the need of making uncertainties seeking a common practice.

Despite the small sample size and the artificial design setting where the studies were performed, the results and conclusions obtained are useful as they invite a discussion about design support platforms and a culture of uncertainty seeking.

Acknowledgments

--

References

Arrow, Holly; Joseph E. McGrath; and Jennifer L. Berdahl (2000). *Small groups as complex systems: formation, coordination, development, and adaption*. Thousand Oaks, CA: Sage Publications.

Blessing, Lucienne T.; A. M. A. R. E. S. H. Chakrabarti; and K. M. Wallace (1998). An overview of descriptive studies in relation to a general design research methodology. *Designers*, 42-56.

Borgue Olivia; Jakob Müller; Alexander Leicht; Massimo Panarotto; and Ola Isaksson (2019). Constraint replacement-based design for additive manufacturing of satellite components: Ensuring design manufacturability through tailored test artefacts. *Aerospace* vol. 6, no. 11, pp. 124.

Brice, Craig (2011). *Unintended consequences: How qualification constrains innovation*. Proceedings of the 1st World Congress on Integrated Computational Materials Engineering (ICME), pp. 241. John Wiley & Sons.

Boujut Jean-François; and Eric Blanco (2003). Intermediary objects as a means to foster co-operation in engineering design. *Computer Supported Cooperative Work (CSCW)*, vol. 12, no. 2, pp. 205-219.

Browning, Tyson R.; and Ranga Ramasesh (2015). Reducing unwelcome surprises in project management. *MIT Sloan Management Review*, vol. 56(3), pp. 53-62.

Chigbu, Uchendu Eugene (2019). Visually hypothesising in scientific paper writing: Confirming and refuting qualitative research hypotheses using diagrams. *Publications*, vol. 7(1), pp. 22.

Claesson Anders (2006). *A configurable component framework supporting platform-based product development*. PhD dissertation. Chalmers University of Technology: Dept. of Industrial and Materials Science.

Diegel, Olaf; Axel Nordin; and Damien Motte (2019). *A Practical Guide to Design for Additive Manufacturing*. Springer Singapore.

Dordlofva, Christo (2020). A Design for Qualification Framework for the Development of Additive Manufacturing Components—A Case Study from the Space Industry. *Aerospace*, vol. 7(3), pp. 25.

Dordlofva, Christo; and Peter Törlind (2020). Evaluating design uncertainties in additive manufacturing using design artefacts: examples from space industry. *Design Science*, vol. 6.

Ellis, Geoffrey; and Alan Dix (2006). *An explorative analysis of user evaluation studies in information visualisation*. Proceedings of the 2006 AVI workshop on Beyond time and errors: novel evaluation methods for information visualization, pp. 1-7. ACM, Venice, Italy.

Elverum, Christer W.; and Torgeir Welon (2015). On the use of directional and incremental prototyping in the development of high novelty products: Two case studies in the automotive industry. *Journal of Engineering and Technology Management*, vol. 38, pp. 71-88; https://doi.or g/10.1016/j.jengtecman.2015.09.003.

Jensen, Matilde B.; Christer W. Elverum; and Martin Steinert (2017). Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. *Design Studies*, vol. 49, pp. 1-31.

Kleinsmann, Maaike; Fleur Deken: Andy Dong; and Kristina Lauche. Development of design collaboration skills. *Journal of Engineering Design*, vol. 23, no. 7 (2012): pp. 485-506.

Kumke, Martin; Hagen Watschke; and Thomas Vietor (2016). A new methodological framework for design for additive manufacturing. *Virtual and Physical Prototyping*, vol. 11, no. 1, pp. 3–19.https://doi.org/10.1080/17452759.2016.1139377.

Goldberg, Chana; Devaiah Nalianda; V Sethi; Pericles Pilidis; Riti Singh; and Konstantinos Kyprianidis (2018). Assessment of an energy-efficient aircraft concept from a techno-economic perspective. *Applied Energy*, vol. 221, pp. 229-238.

Hargadon, Andrew B.; and Beth A. Bechky (2006). When collections of creatives become creative collectives: a field study of problem solving at work. *Organization Science*, vol. 17(4): pp. 484–500.
Henricksen, Karen; and Jadwiga Indulska (2004). *Modelling and using imperfect context information*. IEEE Annual Conference on Pervasive Computing and Communications Workshops, 2004. Proceedings of the Second, pp. 33-37. IEEE.
Mai, Nu Nu; Yoshi Takahashi; and Mon Mon Oo (2020). Testing the Effectiveness of Transfer Interventions Using Solomon Four-Group Designs. *Education Sciences*, vol. 10(4), pp. 92.
MerriamWebster (2021) Dictionary-Concern, Merriam Webster. https://www.merriam-webster.com/dictionary/concern#:~:text=Definition%20of%20concern%20%28Entry%202%20of%202%29%201,The%20actor%27s%20sudden%20collapse%20on%20stage%20caused%20concern. Accessed 27 May 2021.
Mavris, Dimitri N.; Oliver Bandte; and Daniel A. DeLaurentis (1999). Robust design simulation: a probabilistic approach to multidisciplinary design. *Journal of Aircraft*, vol. 36(1), pp. 298-307.
McKoy, Felicia L.; Noé Vargas-Hernández: Joshua D. Summers; and Jami J. Shah (2001) Influence of design representation on effectiveness of idea generation. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 80258, pp. 39-48. American Society of Mechanical Engineers.
Ogaji, S. O. T.; Pericles Pilidis; and Richard Hales (2007). TERA-a tool for aero-engine modelling and management.
Palinkas, Lawrence A.; Sarah M. Horwitz; Carla A. Green; Jennifer P. Wisdom; Naihua Duan; and Kimberly Hoagwood (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and policy in mental health and mental health services research*, vol. 42(5), pp. 533-544.
Passemard, Dan; and Brian H. Kleiner (2000). Competitive advantage in global industries. *Management Research News*.
Porter, Michael E. (1985). Technology and competitive advantage. *Journal of business strategy*.
Raydugin, Yuri (2012). Quantifying unknown unknowns in an oil and gas capital project. *International Journal of Risk and Contingency Management* (IJRCM), vol. 1(2), pp. 29-42.
Ramasesh, Ranga V.; and Tyson R. Browning (2014). A conceptual framework for tackling knowable unknown unknowns in project management. *Journal of operations management*, vol. 32(4), pp. 190-204.
Sawilowsky, Shlomo; D. Lynn Kelley; R. Clifford Blair; and Barry S. Markman (1994). Meta-analysis and the Solomon four-group design. *The Journal of Experimental Education*, vol. 62(4), pp. 361-376.
Seepersad, Carolyn Conner; Jared Allison; and Conner Sharpe (2017). *The need for effective design guides in additive manufacturing.* Proceedings of the 21st International Conference on Engineering Design (ICED 17), vol. 5: Design for X, Design to X, Vancouver, Canada, pp. 309-316.

Stroud, Dick (2002). The impact of the new technologies—Permanent paradigm shift or transitory aberration?. *Interactive Marketing*, vol. 4(2), pp. 144-155.

Struck, Christian; and Jan Hensen (2007). *On supporting design decisions in conceptual design addressing specification uncertainties using performance simulation.* Proceedings of the 10th IBPSA Building Simulation Conference, pp. 3-5.

Subrahmanian Eswaran; Ira Monarch; Suresh Konda; Helen Granger; Russ Milliken, and Arthur Westerberg (2003). Boundary objects and prototypes at the interfaces of engineering design. *Computer Supported Cooperative Work (CSCW)*, vol. 12, no. 2, pp. 185-203.

Sutcliffe, Alistair; and Pete Sawyer (2013). *Requirements elicitation: Towards the unknown unknowns*. 21st IEEE International Requirements Engineering Conference, pp. 92-104. IEEE.

Thompson, Mary Kathryn; Giovanni Moroni; Tom Vaneker; Georges Fadel; Ian Campbell, Ian Gibson; Alain Bernard et al. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology* vol. 65, pp. 737-760; https://doi.org/10.1016/j.cirp.2016.05.004.

Trochim William (2021). Experimental design. https://conjointly.com/kb/experimental-design/. Accessed 27 May 2021.

Valfre James (2012). *Testability modeling usage in design-for-test and product lifecycle cost reduction*. 2012 IEEE AUTOTESTCON Proceedings, pp. 39-41. IEEE.

Yin Robert (1994). *Case study research: design and methods*. Sage Publications, Inc ISBN 0 761, no. 92553, pp. 8.