THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Design for Producibility in Fabricated Aerospace Components

A framework for predicting and controlling geometrical variation and weld quality defects during multidisciplinary design

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Design for Manufacturing and Producibility
in Fabricated Aerospace Components
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Cover:
The cover illustration is a representation of producibility.
Producibility arises from the interaction of two systems design and manufacturing
Producibility becomes tangible in form of manufacturing variation and quality defects

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A mi corazón

Abstract

In the aerospace industry, weight reduction has been one of the key factors in making aircraft more fuel efficient in order to satisfy environmental demands and increase competitiveness. One strategy adopted by aircraft component suppliers to reduce weight has been fabrication, in which small cast or forged parts are welded together into a final shape. Fabrication increases design freedom due to the possibility of configuring several materials and geometries, which broadens out the design space and allows multioptimization in product weight, performance quality and cost. However, with fabrication, the number of assembly steps and the complexity of the manufacturing process have increased. The use of welding has brought to the forefront important producibility problems related to geometrical variation and weld quality.

The goal of this research is to analyze the current situation in industry and academia and propose methods and tools within Engineering Design and Quality Engineering to solve producibility problems involving welded high performance integrated components.

The research group "Geometry Assurance and Robust Design" at Chalmers University of Technology, in which this thesis has been produced, has the objective to simulate and foresee geometrical quality problems during the early phases of the product realization process to allow the development of robust concepts and the optimization of tolerances, thus solving producibility problems. Virtual manufacturing is a key within the multidisciplinary design process of aerospace components, in which automated processes analyze broad sets of design variants to trade-off requirements among various disciplines. However, as studied in this thesis, existing methods and tools to analyze producibility do not cover all aspects that define the quality of welded structures. Furthermore, to this day, not all phenomena related to welding can be virtually modelled. Understanding causes and effects still relies on expert judgements and physical experimentation to a great deal. However, when it comes to assessing the capability of many geometrical variants, such an effort might be costly. This deficiency indicates the need for virtual assessment methods and systematic experimentation to analyze the producibility of the design variants and produce process capability data that can be reused in future projects.

To fulfill that need, this thesis provides support to designers in assessing producibility by virtually and rapidly predicting the welding quality of a large number of product design variants during the multidisciplinary design space process of fabricated aerospace components.

The first step has been to map the fabrication process during which producibility problems might potentially occur. The producibility conceptual model has been proposed to represent the fabrication process in order to understand how variation is originated and propagated.

With this representation at hand, a number of methods have been developed and employed to provide support to: 1) *Identify* and *2) Measure* what affects producibility*; 3) Analyze* the effect of the interaction between factors that affect producibility and *4)Predict* producibility. These activities and methods constitute the core of the proposed Design for Producibility framework. This framework combines specialized information about welding problems (know-hows), and inspection, testing and simulation data to systematically predict and evaluate the welding producibility of a set of product design variants.

Through this thesis, producibility evaluations are no longer limited to a single geometry and the study of the process parameter window. Instead, a set of geometrical variants within the design space can be analyzed. The results can be used to perform optimization and evaluate trade-offs among different disciplines during design space exploration and analysis, thus supporting the multidisciplinary design process of fabricated (welded) aerospace components.

Keywords: Design for Producibility, Variation Management, Quality Assurance, Welding, Aerospace

Acknowledgments

The research presented in this thesis has been carried out at the Department of Industrial and Materials Science (IMS) at Chalmers University of Technology in Gothenburg and at GKN Aerospace in Trollhättan, Sweden. It has received financial support from the Swedish Governmental Agency for Innovation Systems (VINNOVA) and the Swedish National Aeronautics Research Programme (NFFP) through the Wingquist Laboratory. I gratefully acknowledge their financial support.

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Second, I would like to thank my co-authors and some of my colleagues for their comments and our great discussions which have greatly enhanced my research work: Samuel Lorin, Lars Lindkvist, Petter Andersson (GKN), Donatas Kveselys (GKN), Petter Hammerberg, Anders Forslund, Steven Hoffensson, Jonas Landahl, Konstantinos Stylidis, Ola Isaksson, Lars Ola Bligård, and Cecilia Berlin.

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Finally, I wish to acknowledge my parents, my friends outside work and specially my new little family, my partner Markus and my son Oscar. Thank you for your constant and unconditional support. Without that support, I could not have come this far.

Sincerely,
Julia Madrid
Gothenburg, Sweden, June 2020

Appended Publications

Paper A
Vallhagen, J., Madrid, J., Söderberg, R., Wärmefjord, K., 2013. An approach for producibility and DFM-methodology in aerospace engine component development. *2nd International Through-life Engineering Services Conference. Procedia CIRP, 11*, pp.151-156. Cranfield University, Cranfield, UK.

Paper B
Madrid, J., Vallhagen, J., Söderberg, R. and Wärmefjord, K., 2016. Enabling reuse of inspection data to support robust design: a case in the aerospace industry. *14th CIRP Conference on Computer Aided Tolerancing (CAT). Procedia CIRP, 43,* pp.41-46. Göteborg, Sweden.

Paper C
Madrid, J., Söderberg, R., Vallhagen, J. and Wärmefjord, K., 2016. Development of a conceptual framework to assess producibility for fabricated aerospace components. *48th CIRP Conference on Manufacturing Systems - CMS 2015. Procedia CIRP, 41*, pp.681-686. Ischia, Naples, Italy.

Paper D
Madrid, J., Forslund, A., Söderberg, R., Wärmefjord, K., Hoffenson, S., Vallhagen, J. and Andersson, P., 2017. A Welding Capability Assessment Method (WCAM) to support multidisciplinary design of aircraft structures. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, pp.1-19. https://doi.org/10.1007/s12008-017-0429-5

Paper E
Madrid, J., Lorin, S., Söderberg, R., Hammersberg, P., Wärmefjord, K., & Lööf, J. 2019. A virtual design of experiments method to evaluate the effect of design and welding parameters on weld quality in aerospace applications. *MDPI Journal Aerospace*, 6(6), 74. https://doi.org/10.3390/aerospace6060074

Paper F
Madrid, J., Landahl, J., Söderberg, R., Johannesson, H. and Lööf, J., 2018, Mitigating risk of producibility failures in platform concept development. *31st Congress of the International Council of the Aeronautical Sciences*, (pp. 9-14), Belo Horizonte, Brazil.

Paper G
Madrid, J., Andersson, P., Söderberg, R., Wärmefjord, K., Kveselys, D., Lindkvist, L. and Lööf, J. 2020. Automated and interactive evaluation of welding producibility in an MDO environment for aircraft components. 2020. *International Journal on Interactive Design and Manufacturing (IJIDeM) (Submitted*).

Work Distribution

Paper A
Vallhagen and Madrid outlined the concept and main ideas in the paper. Madrid carried out the investigations at the industrial site with close supervision from Vallhagen, Söderberg and Wärmefjord. Vallhagen and Madrid wrote the paper. Söderberg and Wärmefjord contributed by reviewing the paper.

Paper B
Madrid outlined the concept of the paper with the support of the other authors. Madrid carried out the investigations and performed a Six Sigma project as a case study at the industrial partner. Madrid wrote the paper. Söderberg, Vallhagen and Wärmefjord contributed by reviewing the paper.

Paper C
Madrid outlined the concept of the paper with the support of Söderberg. Madrid carried out the investigations and developed the model presented in the paper. Madrid wrote the paper. Söderberg, Vallhagen and Wärmefjord contributed comments and feedback.

Paper D
Madrid outlined the concept with support of Forslund, Söderberg, Wärmefjord and Hoffenson. Madrid performed the literature review and investigations, on which Söderberg, Hoffenson and Vallhagen provided feedback. Forslund contributed to the Case Study by creating the CAD models. Welding simulations were performed at the industrial partner supervised by Madrid and Wärmefjord. Madrid wrote the paper. Vallhagen supervised the "DFA and DFM" Section. Andersson contributed by writing the "Design Space Exploration in Multidisciplinary Design" Section. All authors contributed by reviewing the paper.

Paper E
The conceptualization of the paper and method was outlined by Madrid under the supervision of Söderberg and Wärmefjord. The physical welding experiments were designed by Madrid with support from Lorin and conducted at the industrial partner. The development of the simulation was performed by Lorin in collaboration with Madrid. Hammerberg played the role of DOE expert by contributing together with Madrid to the design and analysis of the virtual experiments. The virtual experiments were conducted by Lorin, who contributed to write parts of the subsections 2.3, 2.5 and 3.2. Madrid wrote the majority of the paper. Söderberg and Wärmefjord reviewed the paper, as well as Lööf who reviewed it from an industrial perspective.

Paper F
Madrid was lead author of the paper, while Landahl wrote sections. Madrid and Landahl instigated the initial ideas, outlined the approach, collected the data, as well as produced the core findings. All authors contributed providing comments to the paper.

Paper G
The conceptualization of the approach and Case Study was carried out by Madrid and reviewed from an industrial perspective by Andersson. Söderberg and Wärmefjord contributed also with insights. Madrid led the Case Study, designed the experiments and perform the analyses with the metamodel with support from Andersson and Kveselys. Kveselys created the CAD models and conducted the welding simulations. The analysis of the results was carried out by Madrid and Andersson. Madrid wrote the paper. Andersson contributed to the writing the industrial MDO environment section. All co-authors contributed by reviewing the paper.

Additional Publications

AP1
Stylidis, K., Madrid, J., Wickman, C., & Söderberg, R. 2017. Towards Overcoming the Boundaries between Manufacturing and Perceived Quality: An Example of Automotive Industry. *50th CIRP Conference on Manufacturing Systems. Procedia CIRP*, 63, 733-738.

AP2
Landahl, J., Madrid, J., Levandowski, C., Johannesson, H., Söderberg, R., & Isaksson, O. 2017. Mediating constraints across design and manufacturing using platform-based manufacturing operations. *In DS 87-6 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 6: Design Information and Knowledg*e, Vancouver, Canada.

AP3
Forslund, A., Madrid, J., Söderberg, R., Isaksson, O., Lööf, J. and Frey, D. 2018. Evaluating how functional performance in aerospace components is affected by geometric variation. *SAE International Journal of Aerospace*, 11(01-11-01-0001), pp.5-26. https://doi.org/10.4271/01-11-01-0001

AP4
Söderberg, R., Wärmefjord, K., Madrid, J., Lorin, S., Forslund, A. and Lindkvist, L., 2018. An information and simulation framework for increased quality in welded components. *CIRP Annals*, 67(1), pp.165-168.

AP5
Landahl, J., Jiao, J. R., Madrid, J., Söderberg, R., Johannesson, H. 2020. Dynamic Platform Modeling for Concurrent Product-Production Reconfiguration. *Concurrent Engineering: Research and Applications (CERA)* (*accepted*).

AP6
Lorin, S.; Madrid, J.; Söderberg, R.; Wärmefjord, K. 2020. A new heat source model for keyhole mode laser welding. Journal Science and Technology of Welding and Joining. (submitted).

Table of Contents

List of Abbreviations

AM – Additive Manufacturing
AP – Additional Publication
ARC diagram – Areas of Relevance and Contribution diagram
CAD – Computer Aided Design
CDOV – Concept Design Optimize and Verify
CE – Concurrent Engineering
CFD – Computational Fluid Dynamics
CPDB – CaPaBility DataBase
CTQ – Critical to Quality characteristic
DFA – Design for Assembly
DFM – Design for Manufacturing
DFMA – Design for Manufacturing and Assembly
DFQ – Design for Quality
DFSS – Design for Six Sigma
DMAIC – Design Measure Analyze Improve Control
DFV – Design for Variation
DoE – Design of Experiments
DP – Design Parameter
DRM – Design Research Methodology
F – M modeling – Function – Means modeling
FMEA – Failure Mode Effect Analysis
FTA – Fault Tree Analysis
IAM – Identification Assessment Mitigation
IMAP – Identify Measure Analyze Predict
IPD Integrated Product Development
KC – Key Characteristic
MDA – Multidisciplinary Design Autmation
MDO – Multidisciplinary Design Optimization
NDT – NonDestructive Testing
NFFP – Nationellt Flygtekniskt ForskningsProgram
OEMs – Original Equipment Manufacturers
PV – Process Variable
RDM – Robust Design Methodology
R – Main research result
RQ – Research Question
SBCE – Set Based Concurrent Engineering
SE – Systems Engineering
VMEA – Variation Mode Effect Analysis
VMF – Variation Management Framework
VOC – Voice of the Customer
VRM – Variation Risk Management
WCAM – Welding Capability Assessment Method

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1 Introduction

This chapter provides the background for the research documented in this thesis, together with the goal and research questions.

1.1 FABRICATION AND THE ROLE OF AEROSPACE MANUFACTURERS IN SUSTAINABLE DEVELOPMENT

The world is in a transformation process driven by sustainability. In the last several decades, the airplane has become a common means of transportation (Boeing, 2019). Nevertheless, the aerospace industry is currently under pressure and needs to assume for social, economical, as well as environmental responsibilities. Therefore, for commercial aerospace manufacturers to achieve sustainable development they need strategies to keep costs, emissions and safety under control (Lee et al., 2001, Kellari et al., 2017). This situation has not only motivated aircraft manufacturers but also governmental bodies and the scientific community to act to reduce emissions. Joint research initiatives, e.g. CleanSky (2019) and, NFFP (2019), are pushing the aerospace industry into rapid development of new technologies to fulfill tougher requirements related to fuel consumption efficiency, product weight and cost. Reducing the weight of every component of an aircraft will reduce fuel consumption and thus the level of CO_2 emitted (Runnemalm et al., 2009).

A strategy already adopted by some aircraft engine component manufacturers to meet the challenge of weight and cost reduction has been fabrication (see Figure 1). The basic idea behind fabrication is to substitute a large cast or forged structure by designing smaller parts that are welded together into a final shape.

First, this solution has opened up for a more attractive supplier market capable of forming smaller structures. Second, this way of manufacturing has broadened up the design space due to the possibility of configuring several materials and geometries, thereby allowing product weight optimization (Runnemalm et al., 2009). Therefore, fabrication has become the strategy by which sustainable development can be adopted, as the same time as this strategy has stimulated new design scenarios.

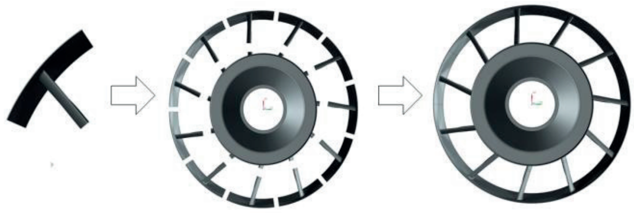

Figure 1 Fabricated aircraft engine component

1.2 MULTIDISCIPLINARY DESIGN IN AEROSPACE COMPONENTS

Aerospace structures in general and aircraft engines in particular are constituted of components with complex geometries highly linked to product performance. These components can be defined as *integrated products* in which multiple functions are satisfied by one single structure (Raja, 2019). A small change of the geometry can have a strong effect on aerodynamic performance, product life, weight, cost, etc. (Forslund, 2016). In addition, these products must fulfill high technical and safety demands to be able to operate. Therefore, requirements from multiple engineering disciplines need to be traded-off during the design process. This situation has motivated the increased adoption of parameterized product models together with multidisciplinary optimization techniques (Sandberg et al., 2017). Different methods and simulation tools are employed to find the optimal value of each design parameter within the design space in order to fulfill every technical requirement.

Nevertheless, in the context of fabricated aerospace components, where a combination of materials, geometries and different ways of product structure are possible, the resulting large design space offers a significant number of design parameters, thus concept variants to be explored and analyzed.

In addition, in early design phases, designers must account for uncertainties in requirements due to the large number of different partners involved in the design process and the complexity of an engine system. To approach uncertainty and complexity, requirements are defined in ranges along with a set of possible design solutions. This strategy is referred as Set-Based Design or Set-Based Concurrent Engineering (SBCE) (Sobek et al., 1999), in which a broad set of design variants, constituting the design space, is considered and analyzed. This set of variants is narrowed down as the detailed requirements are specified and knowledge about the feasibility of the different solutions is generated. Therefore, to handle SBCE in an optimal way, research efforts over the past decade have been concentrated into methods that enable a quicker design space exploration by for example automatizing the design process (Isaksson, 2003, Müller, 2018).

In recent years, multidisciplinary design has progressively benefitted from advancements of computer performance and statistical analysis methods for design space exploration (Ali et al., 2015). The automation capabilities within computer-aided design (CAD) software have improved, enabling design engineers to automatically generate a large number of different design variants (Sandberg et al., 2017). These models can be assessed from the perspective of many disciplines and there are significant achievements in automated analysis within Mechanical Engineering and Computational Fluid Dynamics (CFD) (AnsysWorkbench™, Hyperworks™, Siemens Advanced Simulation™).

However, the virtual assessment of manufacturing capabilities is less developed within the multidisciplinary design process. There are less simulation and automation capabilities to evaluate producibility aspects if compared to other disciplines. Nevertheless, producibility, as a property, also needs to be optimized. A design optimized only from a functional perspective can be expensive or unfeasible to realize during production (Runnemalm et al., 2009).

Thus, the objective is to design and produce robust products in terms of their performance and service variability (reliability concept) (Ebro and Howard, 2016), and also producible products, robust in terms of their manufacturing variation (robustness concept) (Söderberg and Lindkvist, 1999).

1.3 MANUFACTURING VARIATION IN FABRICATED AEROSPACE COMPONENTS

The adoption of fabrication, small cast or forged parts welded together, has some benefits as explained above (e.g. it broadens up the design space and allows for weight optimization) but also has an impact on the manufacturing process. Fabricated aerospace components, in turn, imply a more complex production solution than single structures. The number of parts increases along with the number of assembly and joining steps. In addition, the use of welding often requires pre-operations (machining and tack welding) to prepare the joint for desirable conditions and post-operations, such as heat treatment, thus increasing considerably the manufacturing operation list (see Figure 2). In addition, fixturing processes are required at each operation to lock parts into an optimal position.

If the number of processes increases, geometrical variation and residual stresses stack up, causing quality problems (Steffenburg-Nordenström and Larsson, 2014, Söderberg and Lindkvist, 1999). On top of that, during welding, material transformation and shrinkage occur due to melting and solidification phenomena, causing distortion (Pahkamaa et al., 2012) and weld quality issues with regard to metallurgical defects and weld bead geometry (Jonsson et al., 2011). Therefore, producibility problems in the form of manufacturing variation and weld quality are being aggravated by fabrication.

Figure 2 Some of the most relevant manufacturing operations in a fabricated component

1.3.1 Geometry Assurance and Variation Management

Variation exhibits in every manufacturing situation. Every part that is manufactured has variation in shape and size. Further on, part variation adds to assembly variation. Assembly variation stems from positioning errors when the different parts are assembled and the variation induced by the joining process. The accumulation of variation can lead to manufactured products that do not fulfill assembly requirements in the first instance and functional and aesthetical properties in the second instance, thus influencing the product value or product experience of the customer. Variation in individual parts is not the total problem; it is how variation in parts and assembly processes combine to impact product performance (Söderberg et al., 2016) (Forslund, 2016) (Thornton, 2004). Unfortunately, complex interactions are often not identified until the product is put into production when changes are very expensive. Ultimately, variation can then lead to rework loops, increasing the total production cost and, in some cases, redesign loops increasing drastically the lead time of projects and total product cost (Taguchi et al., 2005). All this translates to customer dissatisfaction. Because of this, in many industries, including aerospace, the management of variation has been identified to be of crucial importance (Söderberg et al., 2006a).

The research presented in this thesis has been carried out in the "Geometry Assurance and Robust Design" group within Wingquist Laboratory at Chalmers University of Technology in close collaboration with the aerospace industry. Virtual Geometry Assurance is presented by Prof. Söderberg as a framework of activities within the product development process with the objective of managing and reducing the effect of geometrical variation throughout the entire product realization process (Söderberg et al., 2016), see Figure 3.

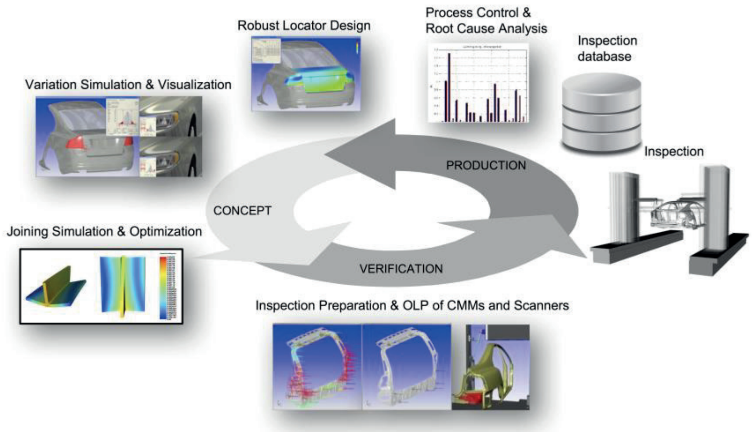

Figure 3 Virtual Geometry Assurance process and toolbox (Söderberg et al., 2016)

However, part geometry and assembly robustness are not the only characteristics composing the total quality for the particular case of welded components. Due to melting and solidification phenomena of a weld bead, other quality characteristics and contributors to variation will determine the final product quality.

1.3.2 The need for producibility assessments in welded aerospace components

In the case of welded aerospace components, the degree of precision required in manufacturing due to tight tolerance makes the effect of weld quality defects, manufacturing variation and particularly geometrical variation especially harmful, thereby compromising product functionality (Forslund, 2016). These types of products have highly integrated designs, in which slight geometrical variations have strong effects on different functionalities. *Geometry affects function.* At the same time, the fabrication process output is dependent on product geometry. The manufacturing outcome is also coupled to design. *Geometry affects producibility.* In the case of welding, the process and equipment are tailored to each design. True craftsmanship is required to find the correct process parameter set-ups to make products fit specifications. Thus, product geometry design also contributes to manufacturing variation (Söderberg et al., 2006b).

Therefore, to mitigate the risk of manufacturing variation, for the particular case of welded aerospace components, there is a need to expand the Virtual Geometry Assurance framework by adding the development of new activities to assure weld quality as well as new methods and tools to analyze and predict producibility during the multidisciplinary design stages of fabricated aerospace components.

1.4 SCIENTIFIC MISSION

1.4.1 Purpose and goal

Within this thesis, producibility is seen as a property that emerges in the interaction between two systems, the product-design and manufacturing systems. Although producibility property is affected from an early design phase, it gets tangible during the manufacturing process when design-manufacturing interaction is physically realized. Two of the consequences of this interaction and the effects of producibility include manufacturing cost and quality, as argued throughout the thesis and discussed by the author in (Vallhagen et al., 2013). Thus, producibility can be conceptualized by considering two dimensions, quality and cost. When designers perform producibility analysis of different concepts, it is not enough with answering the question – *Can we produce this concept?* Manufacturing a product has not the only intention of producing the product, but also to ensure the intent for which the product has been designed, while ensuring that technical requirements are fulfilled without exceeding target cost. This question becomes more relevant in the case of high performance products as those considered under this thesis scope in which delivering performance quality is so important. Thus, to make proper producibility evaluations, questions need to be answered, such as – *Can we produce this concept? Yes, but at what quality level and at what cost?*.

Thus, the purpose of this research is to enable a product realization process in which the balance of all performance disciplinary requirements, including producibility, is optimized to attain high product quality levels at affordable product costs.

To achieve that purpose, the particular goal of this thesis focuses on the quality aspect. Quality is here defined as the concept of process capability, as in Quality Engineering Theory (Taguchi et al., 2005). Quality is achieved when the output variation of a manufacturing operation is within tolerance limits.

Consequently, the goal of this thesis is to provide designers and manufacturing engineers with the support of managing manufacturing variation and ensuring quality earlier during the multidisciplinary design process of fabricated aerospace components.

The starting point would be to model the fabrication process in order to understand what are the sources of variation and how variation is propagated. In this way, producibility drivers can be identified.

Thereafter, support needs to be provided to analyze the producibility of a set of design variants considered in the design space. Thus, methods and tools that can analyze and predict producibility virtually and rapidly need to be developed in order to optimize producibility together with aerodynamics, product life and weight, etc. during the multidisciplinary design process of fabricated aerospace components.

1.4.2 Research Questions

As argued above, in this thesis, the study of producibility is the study of the interaction between design and manufacturing, which can be broken down into two study areas or phenomena. The first area represents the interaction of design-manufacturing from the perspective of design and the design process, while the second area does it from the perspective of manufacturing and the manufacturing process (see Figure 4).

The first study area, producibility during design, is related to the design process and how designers consider the impact that the design has on the manufacturing outcome during that process, i.e., how designers take into account producibility. The research question selected to study this phenomenon is:

RQ1: What are the barriers encountered when making producibility assessments during the ***design process*** *of fabricated aerospace components?*

The second study area, producibility during manufacturing, is related to the manufacturing process, when producibility gets tangible. This includes all physical phenomena that occur during each manufacturing operation, which involve design aspects together with manufacturing aspects (equipment, method and parameters) creating variation, thus jeopardizing quality and ultimately producibility. The research question connected to this phenomenon is:

RQ2: What affects and thus defines the producibility of a fabricated aerospace component during its ***manufacturing process****?*

The third and fourth research questions aim at closing the gap between the first two research questions, i.e. how producibility problems encountered during manufacturing can be analyzed and mitigated earlier during the multidisciplinary design process. Therefore, these last two questions aim at closing the gap between both design and manufacturing areas, as illustrated in Figure 4.

The third research question focuses on the data and information needed to conduct producibility analysis.

RQ3: How can producibility information and data be generated to support integrated development during multidisciplinary design of fabricated aerospace components?

Instead, the fourth research question focuses on the producibility assessment process as a whole.

RQ4: How can producibility assessments be conducted and implemented during the multidisciplinary design process of fabricated aerospace components?

This research question considers two aspects: *RQ4.1)* how to conduct producibility assessments and *RQ4.2)* how to implement these assessments into the larger context of integrated product development and multidisciplinary design.

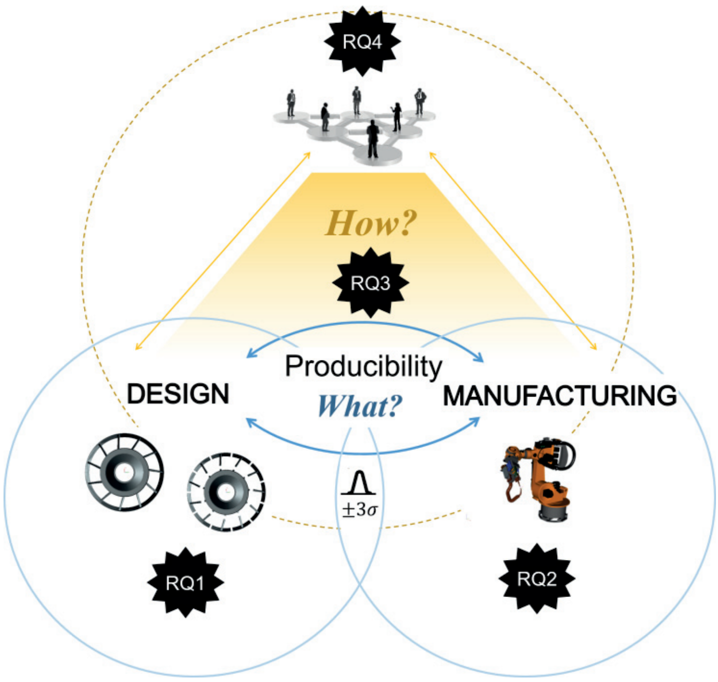

Figure 4. RQs connected to study areas. Producibility can be considered in the design-manufacturing interaction. Manufacturing variation is a consequence of this interaction and the effect of producibility

1.4.3 Scientific and industrial relevance

The research presented in this thesis is characterized by a consideration of both a scientific challenge and an industrial opportunity. Part of the scientific challenge is to deliver results that are relevant and applicable to industrial needs.

Scientific relevance—The scientific goal of this thesis is to provide knowledge of the phenomena selected for study. In the first instance, the goal is to present a detailed descriptive state of the two study areas: 1) how the design process is currently taking care of producibilty; 2) how during the fabrication process producibility problems occur and what cause them. Thus, this thesis contributes to two different scientific fields, Engineering Design and Manufacturing Engineering. In the last instance, the ultimate goal is also to contribute to Quality Engineering with a framework of methods and tools for Quality Assurance and Variation Management for the particular case of fabricated aerospace components.

Industrial relevance—The industrial goal is to 1) increase knowledge of the factors that control quality in welded components and 2) propose a framework (approaches, methods and tools) which supports designers in predicting virtually and rapidly the manufacturing quality of a large number of product design variants during the multidisciplinary design process of fabricated aerospace components.

1.4.4 Scope of the Thesis and Delimitations

The research presented in this thesis is a collaborative project between the Department of Industrial and Materials Science at the Chalmers University of Technology and a subsystem supplier in the aerospace industry. Therefore, the context in which this research has been based on is fabricated aerospace components. Within the operations conducted in the fabrication process of these components (see Figure 2), welding has been the main focus to which most research efforts have been directed.

Nevertheless, as with all research, the aim is to present results that are generally applicable to other cases, thus contributing to new scientific knowledge. Within this thesis, the applicability of results is delimited to highly integrated performance products that are fabricated and assembled employing welding. The focus has been placed on aerospace components. Nevertheless, the results might be applicable to products belonging to other types of industries, which share similar characteristics, as discussed in Chapter 5. In addition, due to the strong similarities between the phenomena that occur during welding and additive manufacturing, results could also be applicable to any highly integrated performance product produced with additive manufacturing or any other process that might imply heating, melting and solidification. The argumentation to the generalizability of research results can be found in Chapter 5 (Subsection 5.4.2).

In addition, as discussed in Chapters 1 and 4 (Introduction and Results), producibility has been conceptualized along two dimensions, quality and cost. Quality is a broad term that embraces many concepts. In this thesis and context, quality is seen as the concept of process capability, as defined in Quality Engineering Theory. Thus, quality is achieved when the output variation of a manufacturing operation is within tolerance limits. The focus of this thesis has been principally on the quality dimension due to the high performance quality requirements on these type of products. Nevertheless, the concept of cost has been discussed and also incorporated in the final study (see Paper G).

1.5 THESIS STRUCTURE

Chapter 1 presents the problem statement and research need. A general and wide societal need is decomposed into specific research goals and questions.

Chapter 2 presents the frame of reference, identifying a research gap and placing this thesis in its scientific context.

Chapter 3 presents the approach and methods used for conducting this research, as well as important considerations by which the quality of the thesis can be evaluated.

Chapter 4 collects the results from the appended papers, interconnects and summarizes them in order to provide a coherent body of findings.

Chapter 5 discusses the results in relation to research questions, existing literature and research gaps. Answers to each research question are provided and comments made regarding their implication for theory and practice. The validity and reliability of the results is also discussed based on the criteria presented in Chapter 3.

Chapter 6 presents the main conclusions of this research and directions for future research.

2 Frame of Reference

This chapter introduces the theoretical background that forms the foundation for the research presented in this thesis.

As argued in the Introduction, the study of producibility compromises the study of two main fields, Engineering Design and Manufacturing Engineering. It is during the manufacturing process that producibility problems become tangible but it is during the design process that these problems must be foreseen and dealt with. However, existing theories in the overlapping area of these two fields are not sufficient to solve the producibility issues encountered in welded high-performance integrated components, as discussed in this chapter. In these types of products, performance quality and robustness are top priorities.

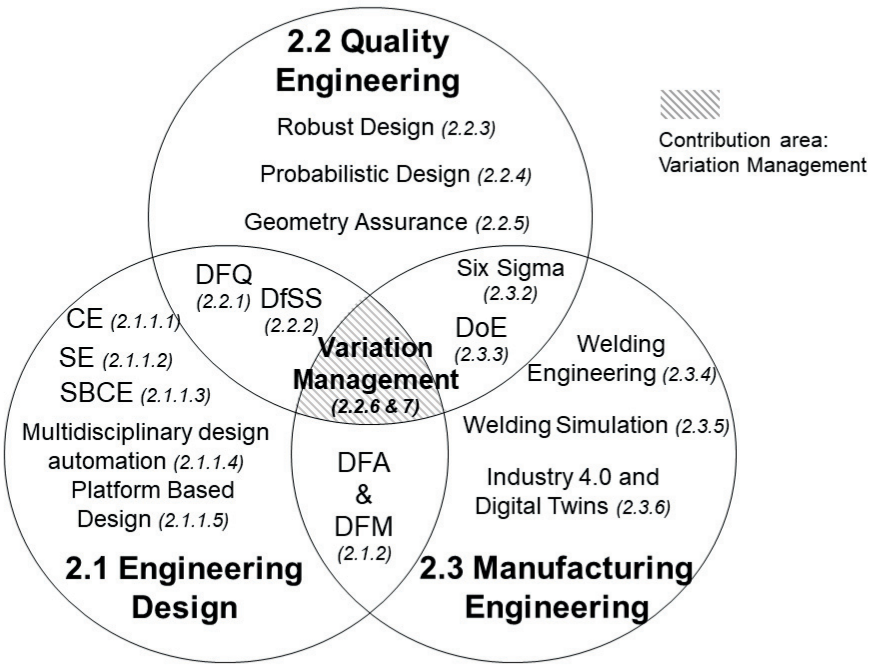

Figure 5 Venn diagram representing areas of relevance and contribution of this thesis

Therefore, to complete the frame of reference for this thesis, a third field, Quality Engineering, needs to be brought into the equation.

The proposed Venn diagram shown in Figure 5 and inspired by the ARC diagram (Blessing and Chakrabarti, 2009) indicates the relevant theories within and between each of these three fields and generates the frame of reference and area contribution of this thesis. The research here presented is interdisciplinary, thus the main contribution is not to a specific scientific field but to the overlapping of three fields, Engineering Design, Quality Engineering and Manufacturing Engineering.

Thus, this chapter has been divided into three main sections according to these three main fields. Each section presents the theories displayed in the Venn diagram in Figure 5. The numbers in the Venn diagram correspond to the numbering of each section and subsection.

2.1 ENGINEERING DESIGN

The Engineering Design field focuses on the design of a technical product (Pahl and Beitz, 1996). Ulrich and Eppinger (2003) employed a more modern and global term, *Product Design and Development*.

To design a product in a systematic way, a number of Engineering Design schools and scholars have prescribed a sequential workflow with which to define the design process (Hubka and Eder, 1996, Ullman, 1992, Ulrich and Eppinger, 2003, Pahl and Beitz, 1996, Roozenburg and Eekels, 1995, Andreasen and Hein, 1987). Figure 6 illustrates the phases of a generic design process as proposed by (Ulrich and Eppinger, 2003). The major phases of a design process include planning, concept development, system design, detail design, testing and refinement and production ramp-up.

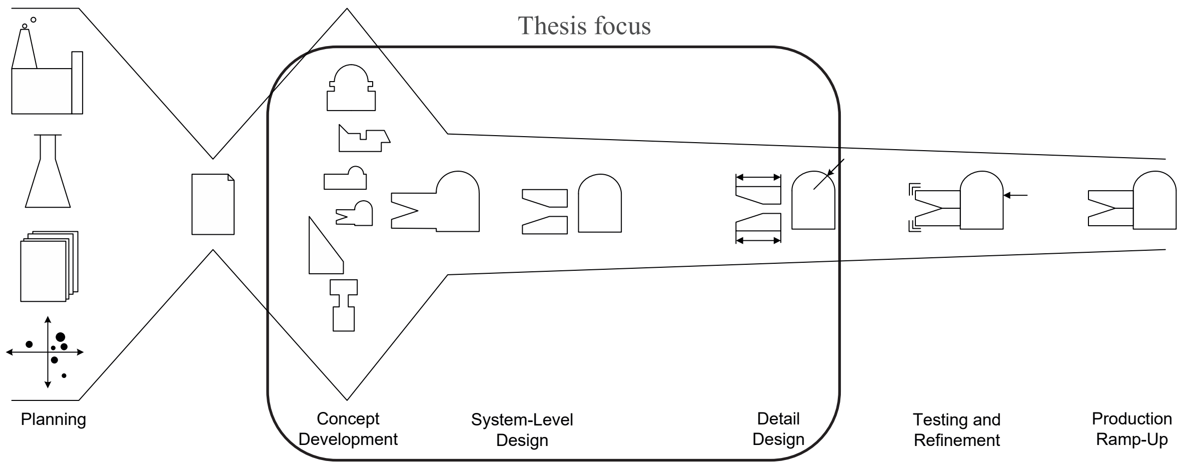

Figure 6. Generic product development process (Ulrich and Eppinger, 2003)

The research work developed in this thesis aims at delivering support to analyze producibility during the conceptual and detail phases, as marked in Figure 6.

In essence, the planning phase of the design process starts with the formulation of required product functions and properties, which in principle make up the list of functional requirements (Hubka and Eder, 1996, Suh, 1990). Based on these requirements, conceptual solutions (function and product structures) are generated, evaluated and selected for further development. During detail design, the details of the design (i.e. the embodiment) are being refined, evaluated and improved in an iterative process until the final design form has been completed and the definitive product layout has been developed.

The iterative process conducted to define concepts and later redefine details in product design is enabled by cycles of synthesis and analysis as discussed by Tjalve (1979), (Andreasen and Hein, 1987), (Pahl and Beitz, 1996), Jensen (1999), and Weber et al. (2004).

During **synthesis**, product characteristics (what Suh (1990) called design parameters), such as structure, form, dimensions (geometry), material and surface characteristics (e.g. roughness) are determined based on required product properties-functional requirements. Examples of product properties are weight, safety, reliability and aesthetic properties. The product properties describe product behavior (i.e. product functionality, product quality) and can only be determined indirectly by the choice of product characteristics. The product characteristics are what designers can create and manipulate directly during the design process. There are also other types of properties, what Hubka and Eder (1996) call relational properties, which arise when the product, considered a system, is related to another system. For example, producibility can be considered a relational property emerging out of the relation of both product and manufacturing systems.

There exist a number of product modeling theories supporting the synthesis process, including the Theory of Technical Systems (Hubka and Eder, 1988), Theory of Domains (Andreasen, 1992), Functional-Means modeling (Tjalve, 1979, Andreasen, 1980) and Axiomatic design (Suh, 1990), etc. For example, Functional-Means modeling is a systematic way of hierarchically decomposing functional requirements (FRs) and modeling the respective Design Solutions (DSs). As a contribution to this theory, (Suh, 1990) introduced Axiomatic Design and proposed the concept of coupled and uncoupled design. Suh considered Design Solutions (DSs) as Design Parameters (DPs). Suh´s independence axiom stated that in a good, uncoupled design each function (FR) is satisfied by only one design parameter (DP). Figure 7 illustrates the difference between coupled, decoupled and uncoupled designs. Thus, to fulfill the independence axiom, the design matrix has to be diagonal or at least triangular.

Uncoupled	Decoupled	Coupled
$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} A11 & 0 \\ 0 & A22 \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$	$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} A11 & 0 \\ A21 & A22 \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$	$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} A11 & A12 \\ A21 & A22 \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$

Figure 7 Design coupling levels as defined by Suh (1990) within Axiomatic Design

After the synthesis process, it comes the **analysis**. During analysis the product system is analyzed in terms of its purpose. Thus, product properties are determined or predicted based on the product characteristics chosen. Analysis activities can be performed through experiments or virtually through simulation tools.

The producibility property emerges from the product-manufacturing system interaction. Thus, to analyze and control this property through product characteristics, designers together with manufacturing engineers need to consider the concurrent design of the product and manufacturing systems which means integrating design and production to support more efficient collaboration.

2.1.1 Approaches to interdisciplinary and integrated product development

The consideration of manufacturing aspects during the design process has been evolving over time. Early on, the attitude of designers corresponded to an "over-the-wall approach"; in which design was walled off from the other product development disciplines (Ullman, 1992). As a result of this intellectual division, the product designer, only responsible for making the design, was working in ignorance of manufacturing process considerations. Once the design layout was finished, it was thrown over the wall to the manufacturing side, which then had to deal with the various manufacturing problems arising from not being involved during the design effort (Boothroyd et al., 2002) & (Ullman, 1992). This one-way communication approach represents a sequential type of design process and a drawback. For this reason and because of market competitiveness, the design process evolved towards a more concurrent way of working (Smith, 1997). In the late 80s, Andreasen and Hein (1987) presented integrated product development as an approach to accommodate the difficulties in managing interdisciplinary development.

Aerospace industry and aircraft manufacturers in particular have a strong focus on performance. The current challenge of getting high performance and multifunction products into such a small envelope implies highly complex and integrated systems. Approaches and methodologies to deal with interdisciplinary and integrated development are fundamental to these cases. Some of the most relevant cases will be outlined below.

2.1.1.1 Concurrent Engineering (CE)

Concurrent Engineering (CE) is mainly seen as an organizational approach within product development with the objective of parallelizing activities that had been performed sequentially, while simultaneously integrating them (Wheelwright and Clark, 1992). Thus, CE implies sharing information within multidisciplinary teams that work together from the requirements stage until the start of serial production. The purpose is to ensure that the requirements of all stakeholders are implemented in the product and to reduce lead-time as the multidisciplinary work is conducted in parallel. As discussed in Paper A, CE is considered to be an ideal environment for producibility implementation.

2.1.1.2 Systems Engineering (SE)

An important part of engineering activities is the identification and break down of requirements together with their verification and validation. Born in the aerospace industry to deal with complex systems, Systems Engineering (SE) is a methodology that focuses on defining customer and internal stakeholder needs and required functionality early during the development process followed by the design and architecture of components and ending with the verification of solutions and validation of the initial requirements identified (Stevens et al., 1998). SE can be used for both product and production development. The key to success is to use a top-down approach in documenting requirements in order to proceed to design synthesis and validation. The V-model (see Figure 8) is used to break down the top level requirements into more detailed requirements at the sub-system and component levels in order to provide a structured framework for development. Iterations between requirements and possible solutions are conducted in particular during concept generation and evaluation to find a balanced design solution. In this context, producibility requirements can be defined in a methodic way, as well as systematically analyzed using different tools at various stages during production development.

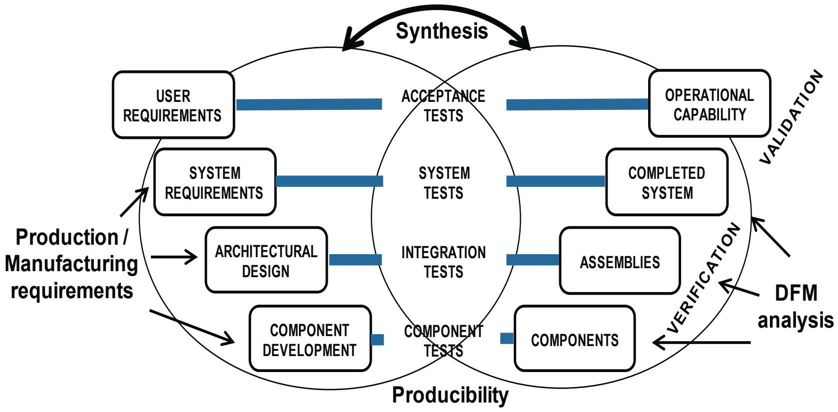

Figure 8 V model from Systems Engineering showing producibility assessment opportunities (Vallhagen et al., 2013)

2.1.1.3 Set-Based Concurrent Engineering or Set-Based Design (SBCE)

Set-Based Concurrent Engineering (SBCE) or Set-Based Design is a design strategy that advocates the exploration of a broad range of alternative design solutions rather than the development of a single solution (Sobek et al., 1999). Alternative design solutions are kept open as possible candidates until enough knowledge has been gained to prove the feasibility of each solution. Thereafter, concepts are gradually eliminated based on facts. This approach allows building and storing knowledge about feasible and unfeasible areas systematically in the design space to reuse it in future projects. The purpose is to make concepts and designs more robust in order to reduce the risk of late changes.

The basic SBCE rules are summarized as follows:

- As constraints are involved, use a funneling process to reduce the number of feasible designs.
- Focus on keeping the design space as open and as long as possible to build knowledge in a systematic way.
- Capture, store and retrieve the knowledge to be used in future designs.

Within the context of this research, design and manufacturing disciplines can define broad sets of feasible solutions in their respective areas. In addition, in the aerospace field, the need to deal with uncertainty during the early stages of the design process makes the exploration of a range of solutions more convenient than developing a single solution. Therefore, SBCE is an advantageous approach with which to be able to manage and treat the producibility aspects since it allows for exploration and knowledge building within the solution space.

2.1.1.4 Multidisciplinary Design Automation (MDA)

The design of aerospace components is intrinsically multidisciplinary. Requirements from multiple engineering disciplines, such as aerodynamics, mechanical engineering and manufacturing, must be traded off against target cost and customer value.

Established approaches begin by parameterizing the component design and defining a large design space by a broad number of design parameters (Saxena and Karsai, 2010). Each engineering discipline analyses every design variant with the help of modeling and simulation techniques. Thereafter, multidisciplinary optimization is employed in order to optimize designs (Sandberg et al., 2017). The idea behind the approach is to virtually explore and analyse as many design variants as possible in order to become flexible and be adaptive to changes of requirements by the OEMs (Original Equipment Manufacturers) at the same time as knowledge is being built (Rönnbäck and Isaksson, 2018). This approach can be ruled by the principles of Set Based Design.

In recent years, Multidisciplinary Design Automation (MDA) has progressively benefitted from advancements in computer performance and statistical analysis methods for design space exploration (Ali et al., 2015, Simpson et al., 2001, Müller, 2018). The automation capabilities within computer-aided design (CAD) software have improved, enabling design engineers to automatically generate a large number of different design variants through the creation of flexible CAD models (Sandberg et al., 2011) (Sandberg et al., 2017). These models can be assessed from the perspective of many disciplines and there are significant achievements in automated analysis within Mechanical Engineering and Computational Fluid Dynamics (CFD) (AnsysWorkbench, Hyperworks, Siemens Advanced Simulation). In addition, with the incorporation of statistical analysis, there is no need to simulate all design variants generated. Different "space filling" methods, for example Design of Experiment (DoE) sampling methods such as Latin hypercube, can be employed to build metamodels (Pronzato and Müller, 2012, Simpson et al., 2001). A response surface-based metamodel is a "model of a model" as described by Simpson et al. (2001), i.e. the regression model built from computer experiments.

With metamodels, the responses of parametric combinations that have not been simulated can be estimated (Simpson et al., 2001).

Multidisciplinary Design Automation speeds up the design synthesis and analysis processes at the same time as it creates knowledge about product behavior in relation to design parameters.

However, the assessment of producibility and manufacturing capabilities based on CAD geometry is, if possible, mostly limited to interactive and manual analysis of a single design. One of the reasons can be attributed to the lack of simulation and automated capabilities for some manufacturing processes. Other reason is the lack of manufacturing process data for producibility evaluations and to feed simulations (Madrid, 2016, Ibrahim and Chassapis, 2016, Tata and Thornton, 1999). Heikkinen et al. (2020) pointed out the lack of historical data in Additive Manufacturing (AM) processes as a challenge to incorporating AM evaluations during Multidisciplinary Design Automation within the aerospace industry.

Nevertheless, during multidisciplinary design, the need to cover the assessment of an extended number of design variants is the greatest. In literature, few automated approaches to assess welding producibility can be found (Elgh and Cederfeldt, 2008, Stolt et al., 2017). These approaches are built on the basis of known welding producibility data.

2.1.1.5 Platform Based Design

Platforms are often employed as a way of reducing manufacturing cost by providing manufacturing with high volumes per parts which are shared among a variety of product variants (Meyer et al., 2018). However, product platform approaches lack support for early-stage manufacturing involvement (Simpson, 2004), which is imperative to avoid over-optimizing on product performance before assessing producibility.

A way forward in research to better support early-stage platform modeling is by employing the reuse of intangible design elements, i.e. functions instead of physical parts, among a set of variants (Alblas and Wortmann, 2014) and increase manufacturing involvement by co-platforming (Michaelis, 2013, Abbas and ElMaraghy, 2016). However, co-platforming approaches lack the inclusion of methods supporting the systematic assessment of producibility of many variants simultaneously. Recent research results indicate that by employing the comprehensive design approach of Set-Based Concurrent Engineering, the modeling of both products and manufacturing systems may be supported during platform concept development using a function modeling technique (Levandowski, 2014).

Building on this research , Landahl (2018) has presented a dynamic platform modeling approach to represent product, production process and production resource varieties together with their interplay. For Landahl (2018), this interplay represents producibility. By executing this platform model, a set of product-production alternatives can be reconfigured.

2.1.2 Design for Assembly and Design for Manufacturing (DFA & DFM)

The need of generic and systematic approaches to consider production aspects during the design process motivated the advent of Design for Assembly (DFA) and Design for Manufacturing (DFM). The core principles of DFA and DFM were established in the 1980´s (Andreasen et al., 1983), (Boothroyd and Dewhurst, 1987) and redefined in the 1990´s (Boothroyd et al., 2002), (Poli, 2001), (Swift and Booker, 2003), (Bralla, 1999). In broad terms, traditional DFA and DFM methods can be classified into two main groups, qualitative methods composed of guidelines and heuristic illustrations and quantitative methods for analyzing design alternatives based on cost and time criteria.

In the field of DFA, guidelines including graphical representations of beneficial and poor practices were developed by Andreasen et al. (1983) and Pahl and Beitz (1996) with the intent of supporting designers in their task to create designs easy to assemble. The basis of DFA quantitative assessments were established by two methods: the Boothroyd Dewhurst DFA method (Boothroyd and Dewhurst, 1987) and the Lucas DFA procedure (Miles, 1989). The main objective of these methods was to suggest redesign improvements for product structure and to assess different alternative designs based on assembly difficulty and time. The ultimate purpose was to optimize time during the execution of the assembly tasks and operations. The principal contribution developed by Boothroyd and Dewhurst was minimum-parts criteria:

- *Does relative motion between parts during the operation of the product exist?*
- *Must the part be of different material?*
- *Must the part be separated to ensure assembly or disassembly?*

Minimum-parts criteria were applied with the intention of suggesting redesign improvements directed at simplifying product structure by reducing the number of parts. As a consequence, the number of assembly steps were reduced and so was assembly time.

The DFM methods emerged after the successful implementation of DFA methods. DFM was thought to be applied at the part design level after DFA had taken care of the product structure design level. This sequence of methods is part of the DFMA methodology (Boothroyd, 1994), see Figure 9.

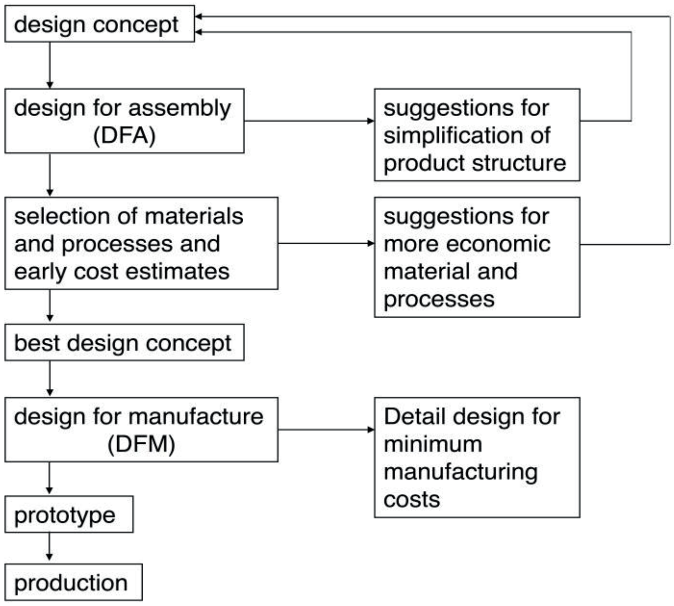

Figure 9 Steps for DFMA methodology (Boothroyd et al., 2002)

The purpose of DFM methods has been to support the design task with the use of manufacturing information and knowledge. In a first step, DFM methods intend to assist manufacturing process and material selection and in a second step, they intend to improve design with the finality of manufacturing cost optimization. As stated in (Boothroyd, 1994), *"Part cost is determined by the selection of the part-processing method and then by the design of the part shape"*.

Notable contributions have been made by Bralla (1999), Poli (2001) and Swift and Booker (2003). Their handbooks provide an understanding of the technical capabilities and limitations of specific manufacturing processes. Bralla (1999) and Poli (2001) guidelines include principles and recommendations to modify designs for subsequent manufacture by citing heuristic examples of good and bad design practices (as the example seen in Figure 10). A later contribution was made by Swift and Booker (2003) and their manufacturing PRocess Information MApS, PRIMAS.

All DFM guidelines reviewed placed the focus on forming processes, such as casting, stamping, injection molding and machining processes. Thus, less focus has been placed on joining methods, such as welding. Even so, some of the DFM guidelines present an overview of different joining processes, including descriptions of processes and equipment (Pahl and Beitz, 1996), (Andreasen et al., 1983), (Swift and Booker, 2003). However, the recommendations provided by these qualitative guidelines with regard to welding are vague. They mainly comment upon the capable thickness to weld and give some basic advice to consider during design. Common examples are: *"design parts to give access to the joint area"; "distortion can be reduced by designing symmetry in parts"; "design simple or straight contours"; "avoid intersecting weld seams";* even *"avoid joints"*.

In addition, cost estimation models were developed to evaluate manufacturability and assess part-manufacturing difficulties (Boothroyd and Radovanovic, 1989), (Dewhurst, 1987), (Dewhurst and Blum, 1989). Cost indices were given for processing the different features using parametric models and a library of manufacturing knowledge bases.

Schreve et al. (1999) presented a DFM cost model for tack welding using a time-rate approach, in which a period of time was assigned to each activity during the tack welding process. This approach allowed a comparison of the total time allocated to two different assemblies. However, this cost model did not focus on output quality.

In the methods described above, the type of products in which DFA and DFM are usually applied are those that can be complex in geometry and that contain large numbers of parts. However, in these products, geometry is not highly linked to functionality (they are not integrated solutions), in contrast to what happens in the type of products studied within this thesis (integrated aerospace components). This fact allows easy geometrical modifications to solve manufacturing difficulties, as well as product structure modifications to solve assembly difficulties in traditional DFM and DFA examples. Because product function is not coupled to manufacturing outcome, in those examples, redesign actions can aim at only reducing time and cost during production, as shown in Figure 10.

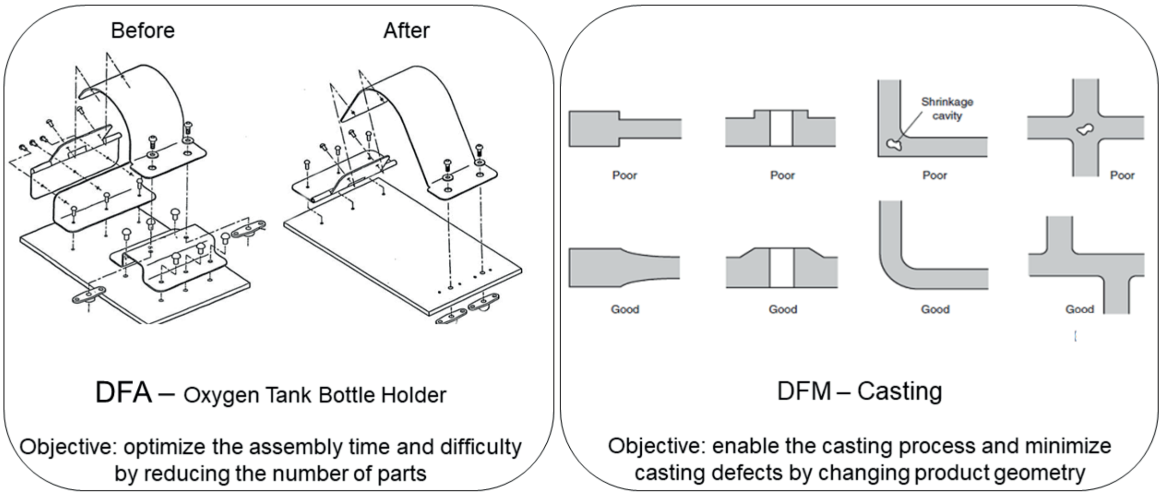

Figure 10 DFM and DFA examples found in literature, in which substantial geometrical and structural modifications have been applied (Boothroyd et al., 2002) (Bralla, 1999).

Nevertheless, as mentioned in the introduction, welded aircraft structures are products made of geometries closely linked to functionality. Highly integrated design solutions in which slight modifications of geometry or structure will have significant effects on product performance (Forslund, 2016). Thus, manufacturing variation of key product characteristics becomes a critical issue. Therefore, for this type of application, producibility criteria must not solely rely on the time and cost spent during manufacture and assembly but also on the quality built into the product, as suggested by the author of this thesis in (Vallhagen et al., 2013) and (Madrid et al., 2016). The objective then becomes reducing quality-related failures during production, thereby minimizing rework costs.

From subsequent research that builds upon traditional DFM and DFA, most of the work has been focused on automating methods and implementing traditional DFM and DFA principles and techniques in computerized environments (Stolt et al., 2015), (Harik and Sahmrani, 2010), (Sanders et al., 2009), (Elgh, 2007), (Sandberg, 2007). Examples include creations of expert systems which incorporate established design guidelines to check on violations of design constrains (Stolt et al., 2015). Within these studies, the integration of DFM using Knowledge Based Engineering (KBE) is commonly explored to achieve design automation (Sandberg, 2007), (Elgh, 2007). As a result, information models have been developed together with CAD-based tool systems aimed at cost optimization (Elgh and Cederfeldt, 2008).

Despite the scant attention paid to joining processes, such as welding, in traditional DFA and DFM, the consideration of welding as the process focus can be found in some studies in recent literature. Some researchers have contributed to Engineering Design by presenting DFM selection tools and methodologies for evaluating alternative designs, materials and welding processing options at early design stages (Tasalloti et al., 2016), (Stolt et al., 2015), (LeBacq et al., 2002), (Maropoulos et al., 2000), (Stolt et al., 2017). All these DFM methods are created on the basis of known manufacturability and cost criteria. They rely on the existence of DFM rules and guidelines that contain knowledge of the limitations of the different materials and welding processes in relation to certain product geometries. However, this information about production capabilities is rarely available as discussed by the author in (Madrid, 2016). In addition, the criteria used by these methods to rank alternative welding methods are based on expert judgment when manufacturing problems are difficult to assess only based on experience.

2.2 QUALITY ENGINEERING

2.2.1 A shift towards Design for Quality (DFQ)

Whereas traditional DFA and DFM were single methods focused on time and cost improvement during assembly and part-manufacturing respectively from 1980s, Design for Quality (DFQ) appeared during the 2000s as a methodology that explicitly focused on the quality objective. When Mørup (1993) first introduced DFQ, he differentiated between *big Q* and *small q* due to the fact that quality means different things to different stakeholders within the product realization process including the customer. *Big Q* represents the product function, the quality perceived by the external customer, whereas *small q* represents the quality perceived by the internal customer, production.

Later on, within the Design for Quality field, Booker (2003), Booker et al. (2005) and Das et al. (2000) analyzed the relationship between design and quality within the DFA and DFM context. Das et al. (2000) introduced the Quality Manufacturability (QM) concept of design as *"the likehood that defects will occur during its manufacture"*, together with a methodology to evaluate designs based on that concept. In fact, the term *design for manufacturability* started to be used more frequently than *Design for Manufacture* because it included quality as the objective concept. Some authors have considered traditional DFM and DFA as islets within the large frame of design for manufacturability, see (Elgh, 2007) and (Das and Kanchanapiboon, 2011). The term quality manufacturability and the DFQ methodology itself exemplify the shift of focus towards quality criteria instead of time and cost. As argued by Das et al. (2000), quality issues are best resolved during the design process, in order to avoid costly redesign and product rework. Therefore, DFQ can be considered a major framework that encompasses all necessary techniques with which to reduce the likelihood of defects occurring during manufacturing from the design process. Within DFQ framework, DFA and DFM methods also occupy their places.

In fact, controlling and minimizing quality failures, risks and manufacturing variation constitutes the entire field of Quality Engineering (Taguchi, 1986). As cited by Taguchi et al. (2005), "*The evolution of quality involves a significant change in thinking from reacting to inspection events to utilizing process patterns in engineering and manufacturing to build quality into the product*". Figure 11 represents the evolution of quality control and the appearance of new methodologies, methods and tools to ensure quality as early as possible in the design process, including Design for Six Sigma, Robust Design, Geometry Assurance and Variation Risk Management, etc.

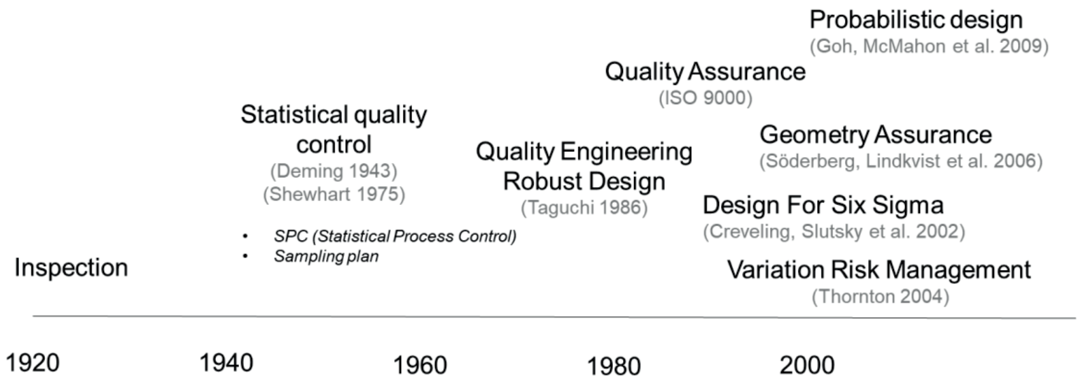

Figure 11 The historical evolution of quality control

2.2.2 Design for Six Sigma (DfSS)

Design for Six Sigma (DfSS) is a framework for applying Six Sigma tools and principles to the design of new products and services. While Six Sigma focusses on improving existing processes, DfSS supports the design of new products that are robust in terms of manufacturing variation (Creveling et al., 2002), (Chowdhury, 2002), (Tennant, 2002).

Therefore, DfSS belongs to the same quality philosophy as DFQ, sharing the same objectives. Nevertheless, DfSS is less of an environment and more of a structured methodology that prescribes where to apply a diverse array of quality tools, whereas DFQ is a broader and fuzzier framework. In a similar way of DMAIC from Six Sigma (to know more about it go to the Subsection 2.3.2 Six Sigma), DfSS presents CDOV, which includes the *Concept*, *Design*, *Optimize* and *Verify* phases. Although a number of variants to CDOV can be found, the main activities and purposes remain the same. Each of these phases connects to the established contents of Engineering Design (Hasenkamp, 2010). First, quality tools are applied to identify customer requirements and generate details of the design. During *Optimize*, robust engineering tools are used to make the product less sensitive to variation. In the final phase, the design is verified to deliver requirements (Creveling et al., 2002). Examples of suggested quality and robust engineering tools are Quality Function Deployment, Design of Experiments, Taguchi methods, etc, some of which will be further developed in this chapter.

In industry, an example of an aerospace manufacturer that has adopted DfSS is General Electric, which has taken significant steps towards implementing probabilistic design by launching DfSS programs in 1995 (Henderson and Evans, 2000) (see also 2.2.4 Probabilistic Design). Another example is Pratt & Whitney, which has launched its own Design for Variation (DFV) initiative, described in detail in (Reinman et al., 2012).

2.2.3 Robust Design

Dr. Genichi Taguchi developed the foundations of Robust Design and Quality Engineering in the early 1960´s (Taguchi, 1986), (Taguchi et al., 2005). The fundamental principle of Robust Design is to improve the quality of a product by minimizing the effect of the sources of variation without eliminating the sources (Phadke, 1989). This principle can be illustrated by the P diagram (see Figure 12). P diagram is a tool proposed by Phadke (1989) to represent a product or process as a system. The system transforms the input (signal factor) into an intended output (response). In addition, there are factors (noise and control factors) influencing such transformation. Whereas control factors are parameters that can be specified, noise factors cannot be controlled by the designer of the system.

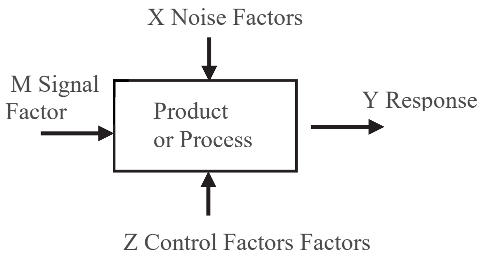

Figure 12 P-diagram (Phadke, 1989)

The objective in Robust Design is accordingly to find the setting of the control factors that minimize the effect of variation on the output or response. Figure 13 illustrates this procedure using the graph of a function. In a sensitive design, the effect of input variation is not minimized. To the contrary, in a robust design, the system minimizes the effect of variation.

Robust Design uses many ideas from statistical experimental design. Three main phases encompass the Taguchi method for Robust Design (Taguchi et al., 2005):

- Concept Design: During the conceptual design of the product, a variety of different solutions including functions and product structure are determined. The different design solutions are then evaluated and compared.
- Parameter Design: During this phase, optimization techniques are performed to find the optimal settings of control parameters.
- Tolerance Design: The goal of this phase is to allocate tolerances balancing the cost associated with tolerances against manufacturing variation cost. A Robust Design strategy is to assign tight tolerances to sensitive parameters and loose tolerances to robust parameters.

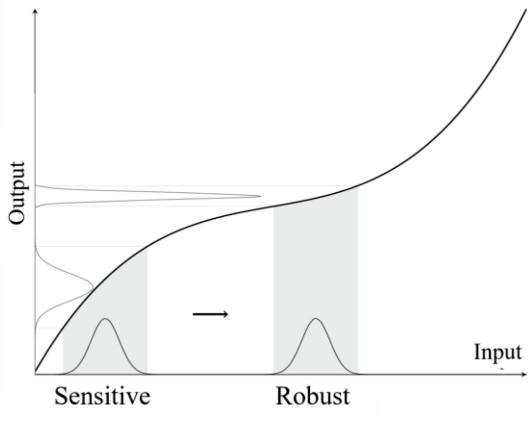

Figure 13 Robust Design illustrated using 1-dimensional function

There exists a more holistic view than the statistical Taguchi methods about Robust Design. Hasenkamp et al. (2009) presented a Robust Design Methodology (RDM) that structures and categorizes Robust Design into principles, practices and tools, see Table 1. Principles relate to the question *Why*, providing the reason or rationale for working with RDM. Practices address *What* activities need to be carried out to fulfill those principles. Tools support *How* to put these practices into action.

Table 1 Principles, practices and tools of Robust Design Methodology (Hasenkamp et al., 2009)

Principles (Why to work with RDM?)	Practices (What to do for RDM?)	Tools (How to do it?)
Awareness of variation (is the basis for systematic robustness efforts)	Focus on the customer	QFD, design reviews, VMEA, brainstorming, cause-effect diagram, flow chart, ideal function
	Identify and understand noise factors	Mathematical modelling, empirical correlations, designer intuition, simulation
	Check the assumptions (e.g. const. error variance or const. % error)	Experience and prior knowledge
Insensitivity to noise factors (is the ultimate goal)	Exploit nonlinearities and interactions	Design Of Experiments, simulation, transfer function, error transmission formula
	Design for insensitivity to noise factors	Smart features, brainstorming, design by analogy, checklists and patent literature, TIPS, literature lacks design synthesis tools
	Use conventional design rules	Experience and prior knowledge
Continuous applicability (to take all opportunities for robustness improvement)	No practices in terms of activities → Organizational aspects affecting continuous application	Integration of RDM into the development process (vs. separate robustness improvement projects)

2.2.4 Probabilistic Design

Traditionally, within the aerospace industry, engineering problems have been formulated to handle variation and uncertainty by including safety factors, in which deterministic simulation practices have been the norm (Zang et al., 2002). However, safety factor approaches are problematic because they often lead to overdesigned products which increase the final cost.

Probabilistic Design is presented as a remedy to address uncertainty and variation through statistical modeling and probabilistic analysis (Goh et al., 2009), (Koch et al., 2004). Thus, Probabilistic Design is an important cornerstone of Robust Design. Probabilistic Design practices can refer to an array of different activities with the objective of converting deterministic problem formulations into probabilistic formulations in order to model and assess anything from variation in materials and operational loads to simplifications and assumptions in models (Forslund et al., 2017b). A few of the methods employed in Probabilistic Design to predict output variation include the Monte Carlo method and Design of Experiments (DoE). The Monte Carlo method is a probability simulation consisting of computational algorithms that employ probability distributions to calculate distributions of possible outcome values through a large number of iterations (Rubinstein and Kroese, 2016). Monte Carlo simulations are also important in the field of Risk Analysis because they provide the decision-maker with a range of possible actions and probabilities to occur. The DoE method will be explained in Subsection 2.3.3.

2.2.5 Geometry Assurance and Tolerance Management

Robust design focuses its efforts on mitigating the effect that control parameters have on system response, as explained earlier. Ishikawa diagrams can facilitate the process of identifying potential control parameters or contributors to variation by helping to structure, classify and document this process (Hasenkamp, 2010). With a focus on uncertainty stemming from the manufacturing process, a holistic framework of contributors to variation and more specifically to geometrical variation was presented by Söderberg (1998), see Figure 14.

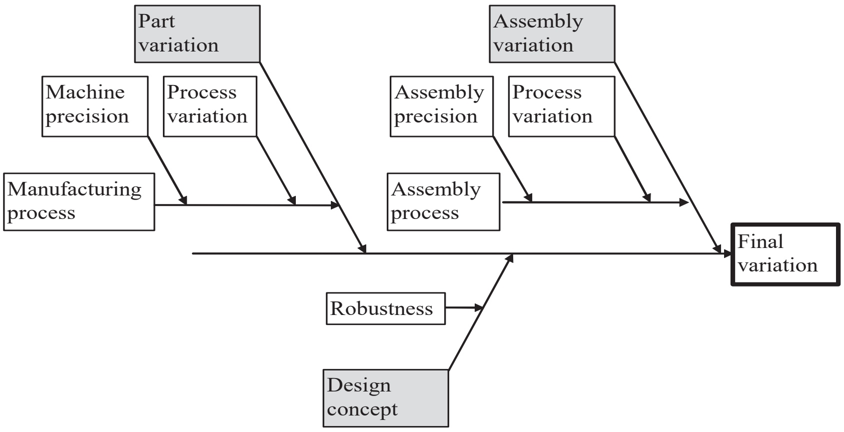

Figure 14 Contributors to final geometrical variation by (Söderberg, 1998)

Part variation comes from the net shape forming process, such as casting, forging, sheet metal forming, etc. This variation, together with variation in the assembly process, lead to geometrical variation of the final product. Furthermore, the robustness of the design influences how variation accumulates and propagates. The final product variation can impact product performance (Söderberg et al., 2016), (Forslund, 2016). Therefore, within the field of Robust Design and Probabilistic approaches, Prof. Söderberg (Söderberg et al., 2006a) (Söderberg et al., 2016) has proposed the Virtual Geometry Assurance process.

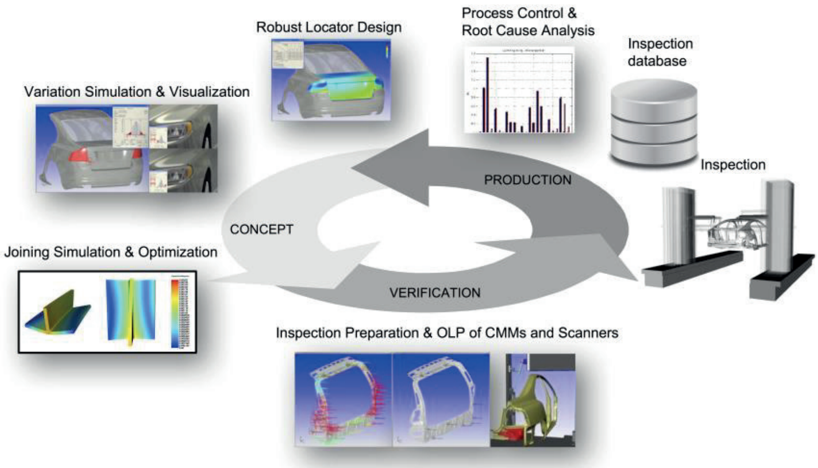

Figure 15 Virtual Geometry Assurance process and toolbox (Söderberg et al., 2016)

Virtual Geometry Assurance (Figure 15) is a set of activities and tools linked to the product development cycle in order to develop robust products, thus assuring geometrical quality. Virtual Geometry Assurance consists of controlling the effect of geometrical variation from the early design phases with the use of Probabilistic Design practices, through verification phases and, finally, production during which experimental data can be gathered to feed design models.

Within the Virtual Geometry Assurance process, tolerance management is supported by the use of robust design tools, such as variation simulations, including the Monte Carlo simulation used in RD&T (2009) software. Variation simulation is a statistical tool used to simulate geometrical variations in critical areas of a part. Monte Carlo iterations are executed to determine the distribution of an output (e.g. critical dimension) based on the given input to the part (e.g. locating schemes, that is how a part is positioned in a fixture, tolerance range and distribution type). Thereafter, contribution analysis can be performed to determine which input parameter contributes the most to output variation. Product robustness can be evaluated and optimized by analyzing sensitivity coefficients, i.e., the influence that the input has on variation amplification and critical product dimensions. Tight tolerances are then applied to sensitive and critical contributors whereas loose tolerances are applied to robust contributors.

2.2.6 Variation Risk Management (VRM)

All methodologies presented so far (DFQ, DfSS, DFV and Robust Design) have the objective of ensuring product quality by dealing with manufacturing variation during design phases. However, taking care of quality of each individual product at all levels can be an endless and costly task, mainly for those industries that develop complex systems, such as aerospace industry. To cope with this problem, Thornton (2004) made a notable contribution presenting the Variation Risk Management (VRM) methodology.

When designing a complex product or system, thousands of dimensions, characteristics and parameters are specified. However, only a subset of these, named as Key Characteristics (KC), is critical to customer requirements, i.e. performance quality. A Key Characteristic is defined by Thornton (2004) as "*A KC is a quantifiable feature of a product, assembly or part which expected variation from target has an unacceptable impact on cost, performance or safety of the product*". Alternative definitions can be found in the Aerospace Standard AS9103 issued by the International Aerospace Quality Group (SAE, 2001). In addition, concepts similar to KC have been used by Phadke (1989), who used "Quality Characteristic" within Robust Design to define the response variable (y) within the P diagram for measuring the quality of a product or process. Moreover, within the DfSS methodology, Critical To Quality characteristics (CTQ) have been used. However, these alternative concepts encompass a larger number of critical issues than KCs do, some of which are not sensitive to variation nor are they related to product features.

The concept of Key Characteristic (KC) is employed nowadays both in the aerospace and other industries to focus improvement efforts only on those product features that have major impact on quality and thus on customer satisfaction (Thornton, 2004), (Whitney, 2006), (Zheng et al., 2008), (SAE, 2001). By working with KCs, the VRM methodology identifies subsets of areas in the product that require significant attention because their variation is critical to quality performance.

VRM methodology is divided into three steps: Identification, Assessment and Mitigation (IAM). During Identification, the KCs that influence critical system requirements are identified. The output of this phase is a variation flowdown (also named KC flowdown), which will be explained in greater detail. The KC flowdown serves as a framework for the Assessment and Mitigation phase. During the Assessment phase, the KCs are prioritized based on their expected risk or cost due to their variation. The final phase, Mitigation, focuses on reducing either sources of variation or their impact on KCs. Thus, the ultimate goal is to mitigate the impact of manufacturing variation on performance quality. Ideally, IAM should be iteratively applied to each stage of the product development to ensure that a product is optimally producible.

The principles of VRM, Robust Design or DfSS are consistent with each other. The VRM methodology takes care of identifying which product systems and characteristics are critical so that Robust Design and DFSS tools and methods can be applied to those critical subsets (Tannock et al., 2007). Therefore, each phase of VRM comprises a number of Quality Engineering tools and methods to support the different phases of execution. Some of the methods include Quality Function Deployment (QFD), Failure Mode and Effects Analysis (FMEA), Variation Mode and Effect analysis (VMEA), Design of Experiments (DOE), etc.

Furthermore, whereas other methodologies have a more general application (e.g. DfSS can be applied to services), VRM focuses on manufactured products, specifically assembled products and complex systems. However, support is not given to a specific type of assembly process, thus welding in particular is not mentioned. In addition, most VRM steps assume knowledge about process capabilities when studies have shown that these data and information are not readily available in some industrial processes (Madrid, 2016), (Heikkinen et al., 2020).

2.2.6.1 KC flowdown

The variation flowdown or KC flowdown is the result of the identification phase of the VRM methodology, which has the goal of creating a holistic view of how quality is delivered through all systems and subsystems of a product. The KC flowdown provides a map for all critical product characteristics at each system level and the interrelationship between them. The variation flowdown process starts identifying the voice of the customer (VOC). From those customer requirements, KCs are derived through each product subsystem and assembly level until the part level has been reached, which finally connects to the manufacturing process KCs, see Figure 16. In this way, the KC flowdown model facilitates finding connections between different KCs and acts as a tool to document and communicate KCs during the entire product development process.

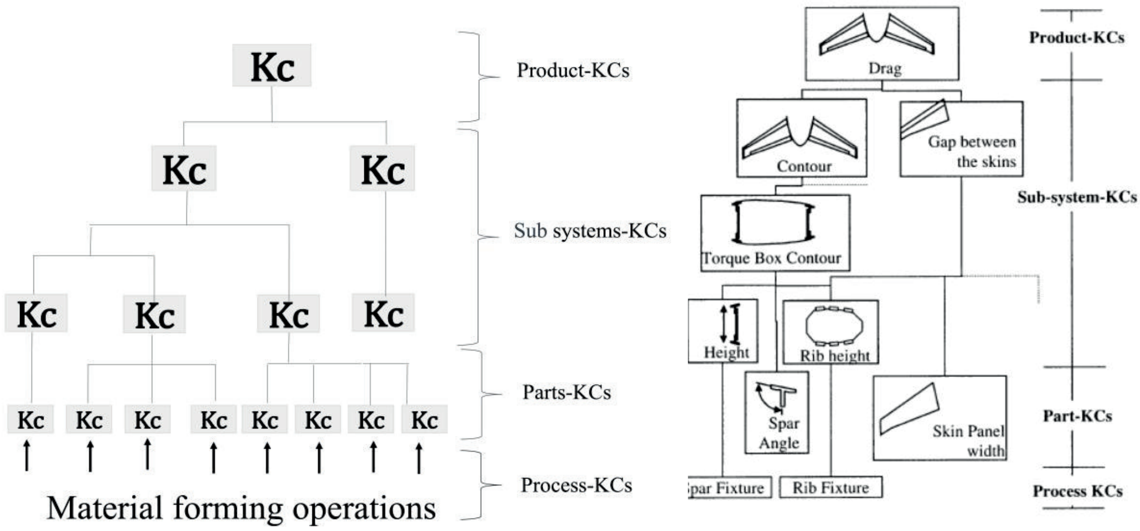

Figure 16 KC flowdown in theory and example in aerospace application as shown in (Thornton, 1999)

2.2.7 Other frameworks and tools for Variation Management

2.2.7.1 Variation Management Framework

The Variation Management Framework was recently developed at the Technical University of Denmark by Howard et al. (2017) with the purpose of explaining and visualizing Robust Design efforts. The four domains proposed by Suh (1990) in Axiomatic Design, Customer, Functional, Physical and Process domains, are represented in this framework. Transfer functions are utilized to map how variation propagates through the different domains. Together with the framework, seven different strategies are proposed to address variation in each domain.

The transfer function that connects the process domain to the design domain only related to variation in process variables (PV) as contributors to variation in design parameters (DP). However, some DPs can also be contributors themselves to production variation and thus to variation in other DPs as pointed out in Chapters 4 and 5 in this thesis.

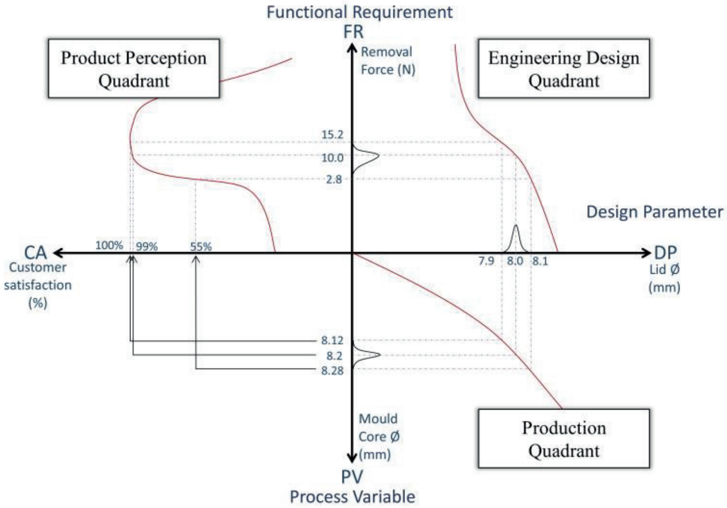

Figure 17 A Variation Management Framework (VMF) as presented by (Howard et al., 2017)

Recent additional research in the area of Variation Management has been focusing on reducing quality failure and related costs (Ibrahim and Chassapis, 2016), (Etienne et al., 2016). Among this research, articles can be found on Cost Engineering for Variation Management (Elgh and Cederfeldt, 2008), (Etienne et al., 2016) and information models for Variation Management (Dantan et al., 2008).

2.2.7.2 Variation Mode and Effect Analysis (VMEA)

Tools such as Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) are used in Risk Management to manage and prioritize risks in the design by identifying potential failure modes or events (Stamatis, 2003), (Lee et al., 1985). In the same way, the Variation Mode and Effect Analysis method (VMEA) supports Variation Management by identifying and prioritizing variation modes (Johansson et al., 2006). This method systematically identifies and prioritizes noise factors or contributors to variation and later assess their effects on Key Characteristics (KCs). First, a KC flowdown is used to break down all KCs into Subsystem KCs, after which an Ishikawa diagram is used to identify all possible Noise Factors.

2.3 MANUFACTURING ENGINEERING

2.3.1 Manufacturing process modeling

Manufacturing variation affects the product quality created during the manufacturing process (Taguchi et al., 2005). Therefore, when the objective is to make quality improvements, a prerequisite for any improvement opportunity or action would be to first understand the context in which manufacturing variation occurs, i.e. understanding what happens during the transformation that occurs during the manufacturing process and its operations. There are several tools for basic process mapping usually found in Operations Management books and Total Quality Management methodology as input and output diagrams and flow charts (Slack et al., 2001), (Sandholm, 2000), (George et al., 2004). These models or diagrams are tools for identifying basic elements of the process, such as process inputs, steps and process outputs (Juran and Godfrey, 1999), thus establishing the various elements processed from operation to operation. Such elements can differ from physical elements to design properties or information. A tool from the Six Sigma methodology, SIPOC (Supplier/ Input/ Process/ Output/ Customer) (George et al., 2004), adds an important element to the basic diagrams. SIPOC incorporates output elements related to customer needs in the mapping, in this way establishing a relation between customer requirements and the Critical To Quality characteristics (similar concept to KC as explained before). However, all these diagrams do not suffice to represent the natural phenomena of variability since they do not identify the factors within the process that control variation.

Instead, as discussed earlier, the P-diagram, from Robust Design, is a model that can serve to represent the manufacturing process as a system. The system is exemplified as a black box, see Figure 12, illustrating the transformation of input M into response Y (defined as a quality characteristic by Phadke (1989)) and how this transformation is not ideal, exhibiting variation due to the influence of noise and control factors.

Continuing along this line, the model within the Theory of Technical Systems (TTS) that Hubka and Eder (1988) created to represent the product as a technical system and the transformation accomplished by such a system can also be used to represent a manufacturing operation. A model depicting a transformation system, operands and a transformation process is presented in Figure 18.

In the same fashion as transformation processes can support product modeling, they can also support manufacturing process modeling.

Attri and Grover (2012) applied the TTS approach to describe the manufacturing system as a facility where transformation processes convert inputs, such as information, material, and energy, into outputs such as information, manufactured products and waste. In fact, in some of their examples, Hubka and Eder (1988) identified the manufacturing equipment as a technical system (TS) executing the transformation process (TrfP) or physical transformation occurring to a product during a manufacturing operation. In these cases, the operand (Od) can be considered the workpiece transformed from an input state (Od1) to an output state (Od2).

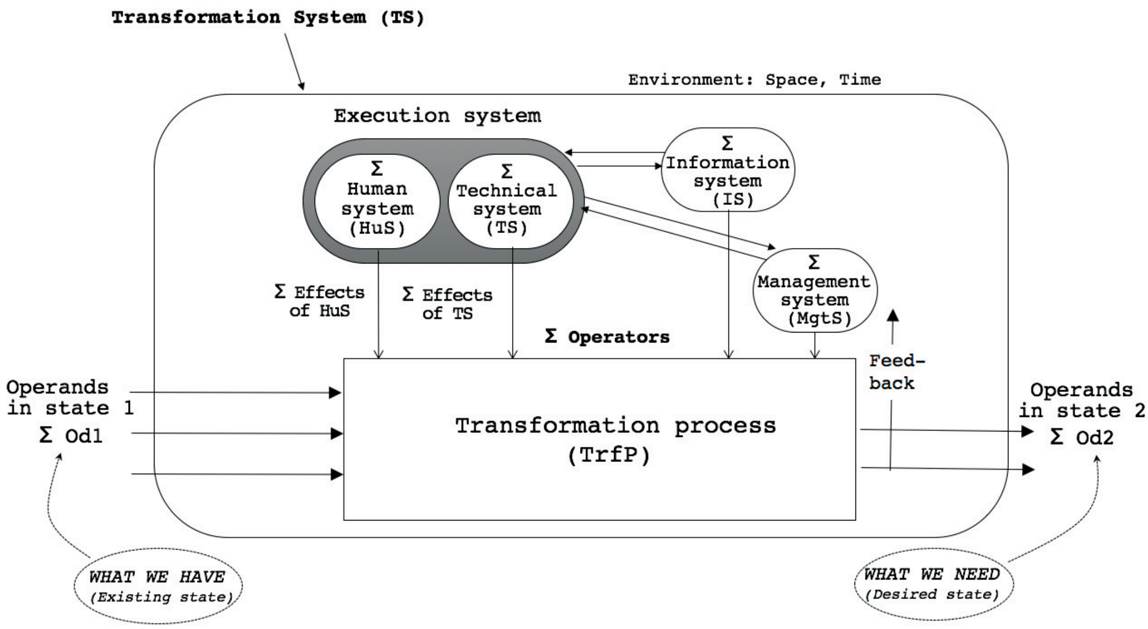

Figure 18 A model of a transformation system, redrawn from (Hubka and Eder, 1988)

In addition, there are a number of “operators” or influencing factors that will affect this TfrP and will have an influence on output response, thus manifesting variation. Examples of those factors are the execution system consisting of two interacting systems, the Humans (HuS) and Technical Systems (TS). In this case, these systems represent the workshop operators and the manufacturing technology used in the operation, respectively. Depending on the level of automation, the interaction between human and technical system would increase.

2.3.2 Six Sigma

With a strong focus on manufacturing process improvement, Six Sigma was born as a methodology that seeks to study an existing manufacturing process to first understand manufacturing process variation, then minimizing and controlling variation within desired levels (Schroeder et al., 2008), (George et al., 2004). Six Sigma prescribes a phase-based approach, DMAIC, consisting of four phases: Define, Measure, Analysis, Improve and Control. Quality tools, some of them previously mentioned, are linked to each phase.

Manufacturing variation is inherent in any process but if it is kept within tolerance limits, it is considered to be acceptable. This is the concept of process capability (Taguchi et al., 2005) and expressed in eq. (1). Process capability (C_p) acts as an indicator of process performance since it relates process variation, represented by 6σ, to tolerance limits (TL).

$$\text{Process capability: } C_p = \frac{TL}{\pm 3\sigma} \quad (1)$$

This concept can represent the quality of design-manufacturing interaction and thus it has been central to this thesis. TL represent design, while 6σ represents manufacturing.

2.3.3 Design of Experiments and Statistical Analysis in manufactuing

A powerful method employed in Six Sigma is Design of Experiments (DoE). As described by Montgomery (2017), DoE is a systematic approach, including statistical tools and experimentation concepts, that allows the determination of individual and interactive effects of various factors that can influence the output-responses of a process. The idea is to design a plan of experiments to maximize information about the behaviour of a process with a minimum number of runs (or experiments). Thus, in DoE, extreme values (the so-called -1 and +1 factor levels) are selected for each factor to create a matrix of experiments. Once the experimental data has been obtained, statistical modeling techniques are applied to obtain a model. The model is utilized to manage input factors in order to optimize the process output. With this information, sensitivity and robustness analyses can also be performed.

DoE is a practice extensively employed to model and optimize manufacturing processes. In Welding Engineering, numerous studies can be found that employ DoE and other statistical and numerical approaches to optimize weld quality for different welding methods (Benyounis and Olabi, 2008, Manonmani et al., 2007, Nagaraju et al., 2017, Caiazzo et al., 2013, Kanigalpula et al., 2016, Siddaiah et al., 2017, Casalino and Minutolo, 2004). The majority of these studies only include welding process parameters, such as power and speed in the optimization. Thus, the interaction of design–welding process parameters is less considered. However, understating the effect of welding set-up parameters and design parameters is required for real application in aerospace components, as discussed by Caiazzo et al. (2013).

In addition, these welding–DoE studies are mainly performed via physical experiments and not via simulation. Thus, there is a lack of metamodels to evaluate welding producibility.

As discussed in Subsection 2.1.1.4, in a context of Multidisciplinary Design, the use of DoE and statistical analysis in combination with simulation for design space exploration has enabled rapid analysis of a large amount of design variants. Automated simulation and metamodels are employed to predict the effect of selected design parameters on product performance. However, the lack of automated simulation and metamodels to evaluate producibility only makes for optimized designs with regard to product performance. Thereby, considering producibility problems too late in the product realization process.

2.3.4 Introduction to Welding Engineering

The objective of this subsection is to introduce the reader to welding engineering because welding has been the key process within the scope of this thesis.

Welding is a fabrication process that joins materials, usually metals, by causing fusion to melt the material. In some welding methods, a filler material is typically added to the base material to form a pool of molten material (weld pool) that cools and solidifies into a joint. The energy source creating the heat to melt the material varies according to the type of welding method used. Examples of energy sources include electric arc, laser and electron beam, among others (Jenney and O'Brien, 2001), (Olson, 1993), (Jonsson et al., 2011).

As a consequence of the melting and solidification phenomena, the material shrinkage causes residual stresses and deformation (distortion). In addition, metallurgical discontinuities are usually formed, such as cracks and pores. Together with the weld bead geometry, these elements constitute weld quality, i.e. the quality of the welding output (Olson, 1993), (Jenney and O'Brien, 2001), see Figure 19.

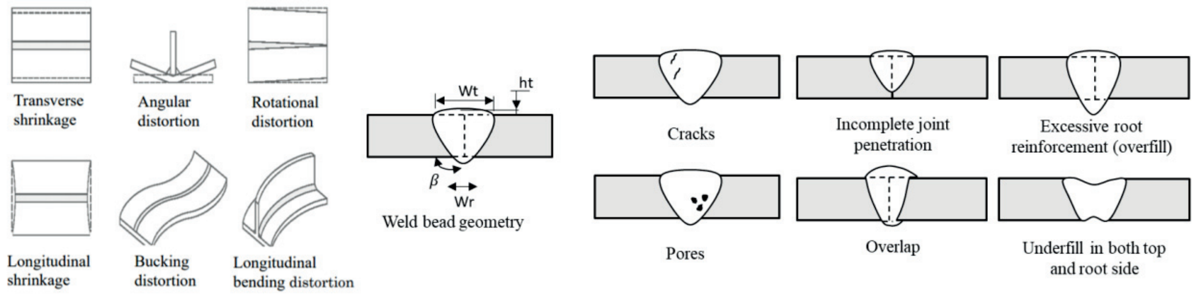

Figure 19 Welding quality outputs

The welding output depends on the input state, which is the result of what has happened to the product in previous operations (see Figure 2). In aerospace applications, high demands are placed on weld quality. Therefore, before the welding operation, a joint preparation is made consisting of machining the edges of the joint and making spot welds by tack welding.

Studies has demonstrated that in the estimation of residual stress due to welding, it is important to consider the distribution of residual stresses due to previous operations (e.g. forming or tack welding) (Olson, 1993), (Steffenburg-Nordenström and Larsson, 2014). In addition, input part variation due to the fixturing or forming processes has also an effect on output distortion due to welding (Wärmefjord et al., 2016).

In addition, welding output quality is dependent of many factors including welding process parameters, weld joint geometry, fixture designs, product form division and product geometry. These factors can be interrelated, some of them playing a role during welding and others during previous operations. Some of them relate to product design and others to the welding process, which makes the welding process sensitive and complex. The overlaying of all these vulnerabilities leads to a small processing window in which the welds have to be made without undesirable defects.

As mentioned in the previous section, research attention in Welding Engineering is primarily paid to understanding the process parameter window and how different welding process variables, such as welding speed, current or voltage, affect welding output (Benyounis et al., 2005), (Hammersberg and Olsson, 2013), (Widener et al., 2010), (Nagesh and Datta, 2002). In these articles, common test examples include rectangular plates. Consequently, understanding the effect of a design and its design parameters on weld quality has been rarely explored. Furthermore, the majority of these studies are performed via physical experiments. There is lack of virtual analysis for welding producibility. Thus, a lack of knowledge on how different product geometries constituting the design space affect welding process output. In the context of multidisciplinary design, this deficit makes the design evaluation process longer and more costly when compared with other disciplines, such as aerodynamics, that have a strong simulation capability. Therefore, questions that might arise when designing high-performance and integrated welded products are: *Why is there a lack of virtual analysis for welding producibility? What is happening in the virtual world concerning welding? To what extend can welding processes be modeled? Can weld quality output be simulated to support product design?*

2.3.5 Introduction to Welding Modeling and Simulation

The modeling of welding processes is not an easy task because it involves the interaction of complex phenomena, such as heating, melting, solidification and vaporization of metals (Olson, 1993, Kazemi and Goldak, 2009, Lienert et al.). Consequently, heat transfer, weld pool dynamics, microstructure dynamics and structural mechanics including stress, strain and deformation need to be considered (Lindgren, 2014, Goldak and Akhlaghi, 2006).

As today, welding simulations are performed and verified in industrial applications to predict residual stresses and distortion. To model these responses, simulation includes thermal and mechanical analyses which are typically solved employing the Finite Element Method (FEM) (Goldak and Akhlaghi, 2006). A FEM simulation consists of three steps: first, modeling of the heat transfer; second, obtaining the transient temperature field; and third, determining the micro-structure dynamics and structural response (Goldak and Akhlaghi, 2006, Lindgren, 2014).

Nevertheless, to this day, there is still a large proportion of characteristics constituting weld quality, such as the formation of metallurgical defects, as well as microstructure and weld bead geometry for which modeling and simulation are at a research stage (Shanmugam et al., 2012, Ai et al., 2017, Hernando et al., 2018, Lindgren et al., 2019b, Xu et al., 2018).

Some of these studies have required the incorporation of Computational Fluid Dynamics (CFD) employing a finite difference or finite volume method in order to analyze the dynamics of the melt pool. However, combining CFD and FEM is a complex problem requiring a long simulation time and is thus often infeasible for certain industrial applications.

Additional aspects of welding simulation under investigation are the effects of process-related welding set-up parameters. Connected to electron beam and laser welding processes, there are studies to simulate the effect of, for example, different gun-to-workpiece distances and beam incident angles (Shanmugam et al., 2010, Kumar et al., 2017). This type of research goes beyond the investigation of the effect of conventional welding process parameters allowing the study of the interaction of the *welding process–product application*. For example, understanding the effect of different beam incident angles on weld quality enables evaluations concerning accessibility questions.

Furthermore, welding simulations have been usually applied to nominal parts. To improve this situation and include the effect of part and assembly variations, research has been performed that combine part and assembly variation with welding simulations to capture the effect of variation stacking up along the assembly process (Pahkamaa et al., 2012), (Lorin, 2014).

Thus, a large part of welding modeling is still in the research stage which makes physical testing and expert judgments still play important roles in industry (Madrid et al., 2017).

So *what are the current applications of welding simulation to support designing of products?* As previously mentioned, welding simulations are commonly employed to predict distortion. In these cases, slight geometrical changes can be made to the design to compensate for deformations. The robustness of locating schemes, i.e. the robustness of the interplay between fixture and product, can also be optimized to minimize deformation (Söderberg and Lindkvist, 1999). Another application employed to support product design can be found in (Wärmefjord et al., 2014), in which form division, i.e. where to locate welds, is optimized to achieve minimal deformation. Besides the above-mentioned, additional applications are mainly focused on welding process improvements. Among them, welding sequence optimization and assembly sequence optimization to minimize distortion can be found in recent research (Wärmefjord et al., 2010, Tabar et al., 2019), (Forslund et al., 2017a). Still, there is potential to employ and develop further welding simulations to support the product design and welding development process in order to achieve better producibility results, i.e. higher weld quality levels after production.

2.3.6 Industry 4.0, Big Data and Digital Twins

With the advent of the 4th Industrial Revolution or Industry 4.0, new opportunities and challenges have emerged. Crucial concepts such as Smart Factory, the Internet of Things and Cyber Physical Systems have enabled advanced information handling (Hermann et al., 2016). Through the utilization of sensors and connectivity between systems, big amounts of data can be generated and shared, so-called Big Data. The creation of adequate systems to provide the right information at the right place and at the right time depending on different stakeholder needs becomes crucial (Åkerman, 2018).

In this context, there is an increased need for manufacturing data and information to be used in probabilistic design, variation modeling, variation analysis tools and simulations to enable Digital Twins and to virtually verify both product and production concepts (Söderberg et al., 2017, Tabar et al., 2019). The concept of a Digital Twin can refer to the “ultrarealistic” digital copy of a physical system that includes additional data and information useful to the current and subsequent product life cycle phases (Boschert and Rosen, 2016). Digital Twins that incorporate manufacturing anomalies can be employed along the product realization phases to perform different types of quality assurance activities and optimization (Tuegel et al., 2011). For example, Tuegel et al. (2011) employed the Digital Twin of an aircraft tail for structural life prediction. Söderberg et al. (2017) proposed a Digital Twin for geometry assurance during design, pre-production and production phases. Aderiani (2019) utilized a digital twin in the production phase to adjust fixture locators in the assembly process and to find the optimal combination of mating parts during the assembly process (selective assembly) to reduce geometrical deformations in the car industry. Tabar et al. (2019) presented a method for welding sequence optimization in the context of a digital twin. Forslund et al. (2018) presented a case in the aerospace industry, in which scanned part data was utilized to create a digital twin to: 1) Evaluate the geometrical variation effects on aerodynamics and thermal and structural performance, 2) Optimize positioning of fixtures, 3) Optimize the parts combinations during assembly (also known as selective assembly) and 4) Optimize design parameters.

For fabricated (welded) products, a Digital Twin can be created and employed in the design phase to develop robust products and distribute tolerances, as well as during production to optimize the assembly/fixturing/welding process in real-time (Söderberg et al., 2018).

However, the industrial implementation of digital twins presents some challenges, as described by Wärmefjord et al. (2020). Performing real time optimization of products and production processes relies on the ability to link large amounts of data to fast simulation (Söderberg et al., 2017). This situation has placed a lot of demands on the availability of adequate manufacturing data (Madrid, 2016) and on methods for smart data handling (Wärmefjord, 2017).

Therefore, there is a need for an information framework to carry pertinent data and information related to the quality control of welded aerospace components.

3 Research Approach

This chapter first justifies suitable frameworks for this scientific work. Further, it discusses the research approach and methods applied in this research project.

All engineering research is driven by the anticipated value of future applications. In this context, it is important to distinguish between fundamental research and applied research (Williamson, 2002). Fundamental research is directed towards theory building, with the main motivation of expanding human knowledge, whereas applied research seeks to solve practical problems (Eckert et al., 2003). This distinction connects applied research more closely to engineering development. However, what defines the borderline separating science from engineering? And, how can we conduct engineering research?

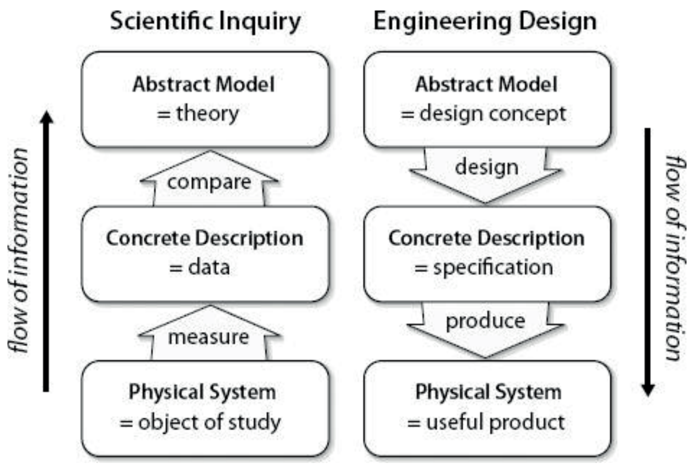

Figure 20 Scientific inquiry vs Engineering Design by (Drexler, 2013)

In his explanation about the difference between science and engineering, Drexler (2013) uses the flow of information as a differentiator (see Figure 20). In scientific inquiry, knowledge flows from the bottom to the top, i.e., from studies and observations of specific parts, general claims can be made and theories developed. In engineering, information flows in the opposite direction. From a broader set of theories and knowledge, engineers can produce specific solutions. Then, how can we do both and how can we combine engineering and science? It feels rational that the answer is to combine both flows of information. Theories, knowledge and hypotheses should be the starting point by which specific descriptions of phenomena and solutions can be generated. Once the specific problem has been studied and solutions proposed and tested, it is time for the information to flow up to either confirm that the hypotheses and theories were correct or to develop new theories and knowledge.

The research presented in this thesis has been carried out in the *Wingquist Laboratory of the VINN Excellence Centre*. Following the research strategy within the *Wingquist Laboratory,* this research has been initiated by an industrial need, associated to a research gap and has thus been conducted in close collaboration with an industrial partner. The mission has been to create knowledge at the same time as providing practical solutions to industrial implementation.

The outcome of this research primarily seeks to contribute to Design Science. The ultimate goal is to provide support to designers when considering the effect of their decisions into the manufacturing quality outcome. Therefore, frameworks for Design Research, such as Design Research Methodology and Action Research, need to be considered. The latter has broader application, extending to fields other than only Design (Coughlan and Coghlan, 2002). Nevertheless, due to its collaborative nature and interaction with the studied object, Action Research becomes relevant within Design, which is fundamental when studying phenomena within the design process.

However, the two study areas addressed in this thesis, as explained in Chapter 1, do not only belong to the design field. In order to provide support during the design phase to manage manufacturing variation and ensure quality earlier in the product realization process, there is a need to first understand what originates that variation. Manufacturing variation originates when product and manufacturing equipment meet during the manufacturing process. Therefore, the second study area focuses on the field of Manufacturing Science.

Addressing two study areas belonging to two different fields (Design and Manufacturing) with their own paradigms makes the communion of two possible research approaches difficult. The aim of this research is to contribute to connecting the two fields, thereby communicating knowledge between Design and Manufacturing. In this dualism, the author has adopted a pragmatic view of the problem in which mixed research methodologies and methods have been used to benefit the problem studied. Therefore, in the coming sections, several research frameworks and methods suitable to address this research problem are presented. Thereafter, the research process applied is also explained, i.e. how these frameworks and methodologies have been applied to the actual research process and which methods of data collection and analysis have been combined. In the final part of this chapter, research quality criteria suitable to verify and validate this research outcome are presented.

3.1 RESEARCH FRAMEWORKS

3.1.1 Design Research Methodology

One of the main issues encountered when conducting Design Research relates to the diversity derived from the multi-faceted nature of the design activity, as pointed out by (Blessing and Chakrabarti, 2009), (Eckert et al., 2003). The diversity of design topics and methods within Design Research may lead to a lack of scientific rigor because of the risk that research may end up in unconnected streams, lacking a common methodology, where anyone can claim the scientific validity of his/her work.

As an action to overcome the lack of scientific rigor within Design Research, Blessing and Chakrabarti (2009) proposed the Design Research Methodology (DRM) "*as an approach and a set of supporting methods and guidelines to be used as a framework for doing Design Research*". The authors argue that Design Research should strive to fulfill two purposes, first, to understand the object of study and second to propose support in the form of tools or methods useful to practitioners. Aligning these two purposes, DRM consists of four stages:

1) *Research Clarification:* The purpose is to clarify the current understanding of the problems that initiated the research project and determine goal, focus and research questions. During this phase, the present and desired scenario are described in a preliminary way. Success Criteria as well as Measurable Criteria are initially defined to evaluate whether research outcomes have resulted in the desired scenario by evaluating the quality of these outcomes.

2) *Descriptive Study I*: With goals and research questions at hand, an increased understanding of the present situation is created through more exhaustive literature analyses and empirical studies. This phase identifies a number of factors that could be addressed to improve the present situation. The formulation of models and theories about the phenomena under study is the main outcome of this phase.

3) *Prescriptive Study I*: Creativity plays an important role at this stage. The researcher should ideally come up with innovative solutions (i.e. supportive tools) extracted from previous findings to improve the present situation and reach the desired outcome.

4) *Descriptive Study II*: The applicability and usefulness of the support proposed is evaluated at this stage. As argued by Almefelt (2005), every proposed tool or method is in a hypothetical-state until its usefulness is proven in its proper context. Through the success and measurable criteria, the ultimate aim of the final stage is to assess whether the support proposed has indeed improved the present situation.

The Success and Measurable criteria for this project have been discussed in Subsection 5.3.2.

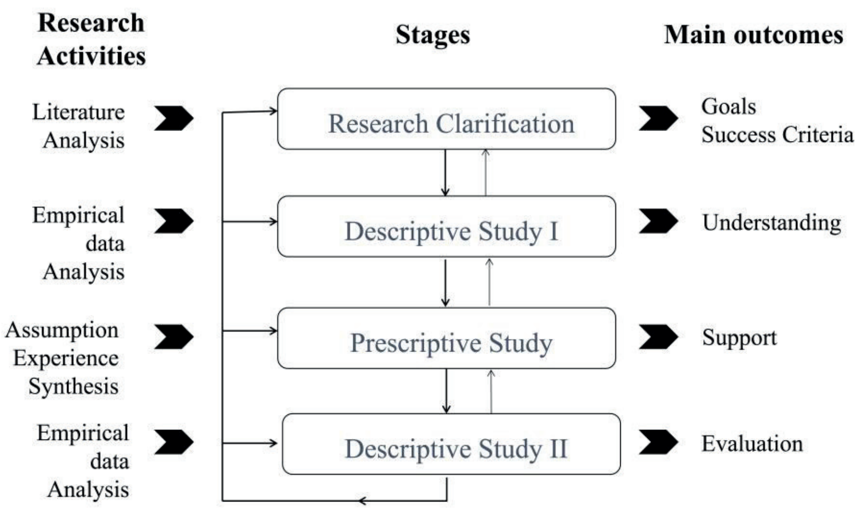

Figure 21 The DRM framework, redrawn from (Blessing and Chakrabarti, 2009)

The four stages presented in DRM do not necessarily need to be followed in a chronological order nor do researchers need to perform all stages during a single research project (Blessing and Chakrabarti, 2009). Depending on the situation at hand and the maturity of the research topic, some phases may need more attention than others.

Because of the attempt of this research to contribute to and impact the Design field, DRM has had a central role as a research framework. DRM has provided a structure to this research project (see Section 3.4), as well as successful and measurable criteria with which to evaluate the quality of the results (see Sections 3.3, 5.3 and 5.4).

3.1.2 Participatory Action Research

The objective of participatory action research is to contribute to the solution of a practical problem in a real world situation (Wadsworth, 1993). There is a dual commitment to study a system and concurrently collaborate with members of the system in transforming it in a desirable direction (Blessing and Chakrabarti, 2009).

The fundamental process prescribed in participatory action research is cyclical in nature with iterations of planning, acting, observing and reflecting for the purpose of guiding the research process (Whyte, 1991). The underlying goal is to understand the situation and produce a supportive action to improve the situation which will be evaluated later on. Thus, the main steps of Action Research show a strong similarity to DRM. However, this methodology prompts a shorter and larger number of iterative cycles than DRM and has usually been employed in management fields (Coughlan and Coghlan, 2002).

The seed initiating the research activity conducted in this thesis was a problem in the aerospace industry. Thus, the objectives of this thesis have been to produce knowledge and action directly useful to members of industry and empower them through the process of applying their knowledge, thereby aligning these efforts with the objectives of Action Research, justifying its use. Action Research is well suited to explain research in an industrial context where solutions are proposed and put in realization and knowledge is gain through the involvement of experts and practitioners (Ragsdell, 2009). Thus, it has served as relevant inspiration to this research.

3.1.3 Case Study Research

There have been traditional prejudices against the use of Case Studies as a research strategy. One concern has been the lack of rigor if they are to be compared to experiments or surveys. However, research evidence and researchers, such as Yin (1994) and Flyvbjerg (2006), have defended Case Studies as an appropriate research strategy, which does not necessarily need to be mutually exclusive when applied along with other strategies.

Yin (1994) gives a technical definition of a Case Study presented in two parts. The first part of the definition relates to the scope of the Case Study. A Case Study is preferred when the researcher has the aim of investigating an occurrence over which he or she has little control. This is when the phenomenon to be studied cannot be isolated from the context and thus, cannot be reproduced in a laboratory setting. The second part of the definition given by Yin (1994) defends the Case Study as an all-encompassing method with the logic of planning specific approaches to data collection and analysis. The strength of a Case Study is that it allows the researcher to gather evidence by combining different methods, such as documents, interviews, direct observations, etc.

This thesis contributes to the scientific field of Design. Within Design Research, the phenomena studied relate to events that occur during the design process. In this thesis, the author studies phenomena especially related to the design and fabrication process of products with singular characteristics. These products include welded and integrated products of high performance. The nature of the problem under investigation makes the choice of the Case Study as a research strategy self-evident because the author is interested in understanding producibility problems in fabricated structures and how to make producibility evaluations during design. These phenomena can only be studied in the field. In addition, a combination of sources and type of data (qualitative and quantitative) is appropriated for the kind of complex problem studied in this thesis. In the phenomena studied, many variables that need to be considered are involved and interconnected, thus it is not enough to include only one data source to provide evidence in support of the claims made. Therefore, the author has explored the Mixed Method approach to reinforce the outcome results of Case Study-based research.

3.1.4 Mixed Method Research

The differences between qualitative and quantitative research have been broadly discussed by such authors as Blessing and Chakrabarti (2009), Maxwell (2012), Given (2008), Creswell and Clark (2011) and Creswell (2013). Both terms can refer to the type of questions addressed, data collected, analysis method used or research approach.

Research that includes both qualitative and quantitative approaches, including both data and methods, is called *Mixed Method Research* (Creswell and Clark, 2011). Within a pragmatic stream, authors like Yin (1994), Blessing and Chakrabarti (2009) and Creswell (2013) defend the viewpoint that a combination of qualitative and quantitative approaches provides the richest picture, addressing the various factors involved in the phenomenon under study by using the method that is most suitable for each.

Among the six Mixed Method Research Design types identified by Creswell and Clark (2011), Convergent Parallel Design has been the method that related most directly to the research presented in this thesis. Both quantitative and qualitative data have been collected and analyzed in parallel and compared, resulting in a convergent interpretation. This method is more efficient and allows a pragmatic way of working in which the two sets of results merge into a larger understanding.

3.2 RESEARCH DESIGN: applied research process and methodology

This section illustrates how the research has been designed and conducted. As defined by Yin (1994) *"A research design is the logic that links the data to be collected (and the conclusions to be drawn) to the initial questions of a study"*. Thus, a coherent research approach is one in which the structure and connections between research goal, questions, activities, methods, results, verification and validation support one another to build an integrated whole. The research approach (its structure and connections) is represented in Figure 22 and Table 2.

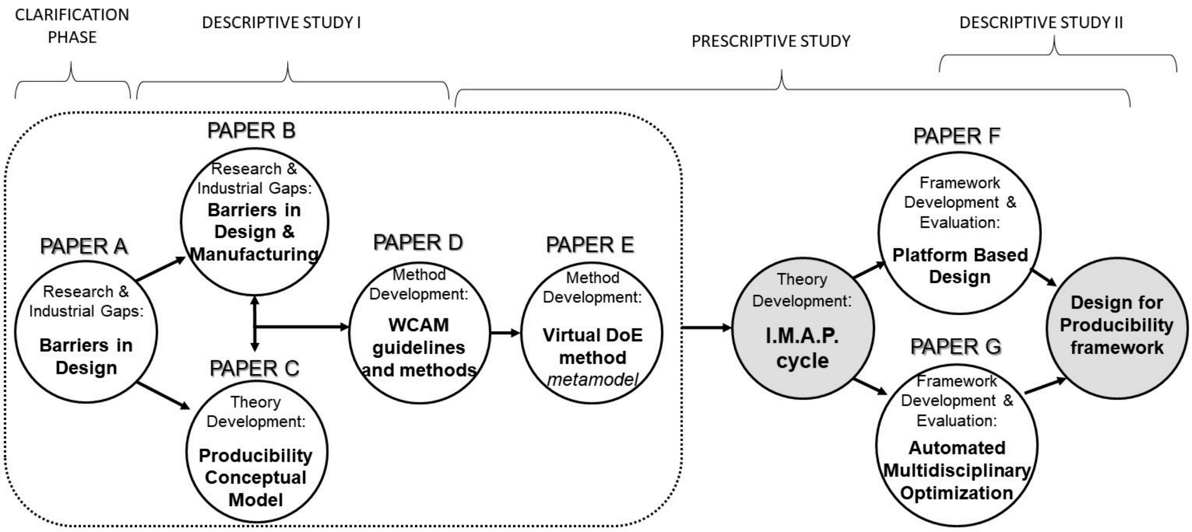

Figure 22 Research process progress and research achievements

Figure 22 illustrates the progress of the research process. Each circle symbolizes an achievement in terms of research results. The seven papers appended are presented in white circles. The grey circles represent relevant research results, which have not been explicitly published in a paper but have been published in this thesis (see Chapter 4, main research results, R8 and R 11 in Subsections 4.2.8 and 4.2.11). Stablished connections between research achievements depicted in Figure 22 show that research has been conducted progressively. Each research study has been built upon previous achievements, thus enduing the research progress with a longitudinal nature.

On a top level, the research process is divided into main stages in accordance with the Design Research Methodology (DRM). Paper A covers the Clarification Phase during which preliminary research questions and success criteria with which to evaluate the research quality are formulated. Descriptive Study I has been conducted through the studies carried out in Papers A, B, C and partly Paper D in which research and industrial gaps have been identified. Additional insights from Papers E, F and G have also contributed to Descriptive Study I. From the understanding gained about the barriers in both fields, Design and Manufacturing, a producibility conceptual model was developed from the theory presented in Paper C. Paper D represents the transition to the Prescriptive phase. During this phase, supportive methods and tools were developed and presented in Papers D and E. In addition, the research outcome achieved until this point has served to formulate a producibility control cycle (I.M.A.P. cycle) contributing to theory building. The implementation of the producibility control cycle was tested in two product development environments in Papers F and G, respectively. The research conducted in both papers has prompted the development of the Design for Producibility framework, as well as served as initial research evaluation studies. Thus, the final DRM phase, Descriptive Study II, has been initially addressed in the F and G Papers.

Although Figure 22 illustrates a linear execution of the DRM stages, which shows coherence with the overall picture, the research work has been performed in iterative cycles. The Research Questions (RQs) were initially formulated during the clarification phase and have been reworked in parallel ever since. The iterative cycles are implicitly shown in Table 2, which connects the seven papers to the specific DRM phases and the RQs to which they contribute. The sizes of the plane symbols in Table 2 indicate if the contribution has been either strong or weak. The multiple iterations between the descriptive and prescriptive studies have allowed a concurrent way of working, in which studies and research activities have been aiming at answering the research questions continuously.

There are four research questions governing this research (to review the RQs, please refer to Chapter 1, Subsection 1.4.2). The first two questions are descriptive. The RQ1 contributes to the Descriptive Study I focusing on the Design field, whereas RQ2 focuses on the Manufacturing field. The third and fourth questions are connected to the Prescriptive Study. RQ3 focuses on the development of methods, whereas RQ4 focuses on framework development. In addition, the first aspect of RQ4 is formulated to deal with implementation and validation, thus contributing to Descriptive Study II.

The research presented in this thesis has been connected to the same continuous research project. The initial research problem, originating in the aerospace industry, was formulated concurrently with an industrial partner. During the initial descriptive studies, case studies were chosen over laboratory studies with which to describe and understand the phenomena within design and manufacturing. Moreover, a control environment could not accurately reproduce the phenomena studied, besides the high experimental cost that this would entail. Therefore, a specific component of a turbofan engine, the Turbine Exhaust Case (TEC), has been chosen as a general case around which to perform the research and study the problem. As illustrated in Figure 22, the research process has a longitudinal nature, in which the various studies reflected in the different papers have focused on different variants of the same case. Three TEC variants (in this thesis named Products I, II and III) have been studied to understand similarities and differences. Product II has been the generation following Product I, in which producibility issues were better handled. Both Products I and II were in production stages. Product III is the newest generation of TEC and is still in a conceptual design phase, thus presenting new challenges. After sufficient knowledge was gained, studies were better able to isolate phenomena. Thus, experimental studies, including physical testing and simulation, were chosen as research strategies.

Table 2 Research Design: connection between DRM phases, RQs, data collected and results. **✈** Strong contribution; ✈ Low contribution

DRM phases	Related RQs	Paper A	Paper B	Paper C	Paper D	Paper E	Paper F	Paper G
Research Clarification		**✈**						
Descriptive Study I	RQ1 (focus on Design)	**✈**	**✈**		✈	✈	✈	✈
	RQ2 (focus on Manufacturing)	✈		**✈**	**✈**			
Prescriptive Study	RQ3 (methods)		✈		**✈**	**✈**		
	RQ4 (RQ4.1 cycle and RQ4.2 framework)						**✈**	**✈**
Descriptive Study II	Validation						✈	✈
Data type		Qualitative	Qualitative & Quantitative	Qualitative	Qualitative & Quantitative	Quantitative	Qualitative & Quantitative	Qualitative & Quantitative
Data Sources Data collection methods		-Literature review -Internal documents -Informal discussions -Semi-structured interviews -Questionnaire -Observations	-Literature review -Internal documents -Interviews -Observations -Manufacturing data	-Literature review -Internal documents -Interviews -Observations	-Literature review -Internal documents -Interviews -Observations -Welding Simulation	-DoE tecnhiques -Welding experiments -Welding Simulation	-Literature review -Engineering rules -Simulations	-Discussions with practitioners -DoE tecniques -Metamodel -Welding simulation

Table 2 presents an overview of the research applied in each paper and how it contributes to answer the different RQs and DRM phases. Qualitative data have been predominating in the first studies of descriptive nature, whereas quantitative data played a more significant role when moving towards prescriptive studies. Overall, the application of Mixed Methods research has been governing the entire research process.

3.2.1 Data collection methods employed and data sources

The Mixed Method Research approach consists of combining data collection methods and sources, and selecting the most appropriate in each case. Adopting a pragmatic approach by combining and converging data increases the strength of the results to support evidence. Below, the author presents an array of data collection methods and data sources, together with a description of how these methods have been generally applied in this research (for Papers´ specifics see the bottom part of Table 2).

Literature review: Reviewing written resources for data collection has been a central aspect of this thesis. Scientific literature and company internal documents have been employed as sources. An initial literature review has been performed to clarify and better define the research problem addressed. This has allowed the author to find initial research gaps and industrial barriers to formulating new and more specific goals within the project. Literature reviews can accomplish several purposes (Creswell and Clark, 2011). Besides the continued use of literature reviews to find research gaps and shape improved research questions, this method has also been employed for theory and method development. In addition, literature reviews have been used as benchmarks for comparing the results with the findings of other researchers.

The academic publications employed in the different literature reviews have been found using various databases, such as SCOPUS, Web of Science and Google Scholar. In addition, backwards and forwards snow balling procedures (Wohlin, 2016) have been conducted from relevant articles in the field.

Interviews: One of the main sources of case study information is the interview (Yin, 1994). The interviews can be designed in various forms, depending on the purpose. A common classification differentiates between three types (Bryman and Bell, 2015): fully structured interviews, semi-structured interviews and unstructured interviews. Within this research project, three types of interviews have been applied. Unstructured interviews have mainly been conducted in the beginning when the purpose was to explore the research topic within the industrial organization. Semi-structured interviews have been the most commonly employed method because it was difficult to formulate closed questions to gather all relevant information required due to the complexity of the topic. In addition, this approach made the respondent feel more comfortable due to its conversational nature. The researcher proved to obtain richer information because of this format. Nevertheless, fully structured interviews with closed questions have also been used when the purpose has been to find answer patterns. A questionnaire, which may fall under this category (Blessing and Chakrabarti, 2009) (please note difference from survey), was used during the Master thesis work conducted by the author.

During the interviews, mediating tools have been used for the purpose of enhancing discussions and understanding of both parties, respondent and interviewer. A mediating tool is a stimulus, a better way of visualizing the subject under discussion, allowing focusing on the specific product or idea on which the researcher is interested (Dagman et al., 2010). Some examples of mediating tools used in this research include: images and prototypes of the product, the weld cross-section under study and the model presented in Paper C (see Figure 26).

The majority of the interviews have been individual. However, several interviews were made in pairs, a way of enhancing conversation. A group interview was performed in the study covered under Paper B. When possible, interviews have been audio-recorded. During interviews performed in the workshop, audio-recording was not possible due to the noisy environment. However, instant notes were taken.

Observations: this method has been central when studying the effects of producibility during the manufacturing process. A meaningful part of the manufacturing process has been observed and mapped, especially the manual tack welding and robot welding operation. Real time observations were conducted combined with simultaneous verbalization, i.e. when operators speak loudly while working in order to give an explanation of each step of the process (Blessing and Chakrabarti, 2009). Observational notes were taken at each moment together with reflective notes, in which the researcher recorded her own reactions and thoughts. Recurrent observations of videos about the robot welding cell were made together with welding experts to better understand phenomena.

Welding experiments: Welding experiments have been conducted at the corporate-University West research facilities in Trollhättan. The main purpose of these experiments has was to develop welding simulations to study specific phenomena. For welding experiments, Bead on Plates (BOP) welds were performed. Thereafter, an etching test was applied to the BOP-welds to reveal weld bead geometries. This test, conducted at company facilities, involved cutting each specimen transversely to the weld axis and applying an etching solution, which allowed inspecting the exposed surface. Thereafter, an image processing software was applied to measure the areas of the weld beads.

Simulations: Simulation software, including welding simulation in MSC Marc, welding and variation simulation in RD&T and path planning simulation in IPS, has been used as a method with which to perform virtual experiments to better understand manufacturing variation and producibility phenomena. In this case, quantitative data was generated.

DoE techniques: The design and plan of virtual experiments were supported with the use of different DoE techniques, such as Optimal Design (Goos and Jones, 2011) and Latin Hypercube (Pronzato and Müller, 2012). By applying these DoE techniques, the experimental design matrices, containing the descriptions of the different experiments or runs, have been produced customized to the characteristics of each specific study. In Paper E, DoE was employed to develop a metamodel. The metamodel generated can represent process capability data. In Paper G, the metamodel has served to predict the weld quality output of new design configurations upon a total new design case scenario.

Inspection data: Another source of quantitative data has been manufacturing inspection data. Since these data have been collected by someone else and for a different purpose, these are considered secondary data. However, these data were useful to study both variation phenomena during manufacturing as well as the utilization of such a data during the design process.

Engineering rules: The concept of engineering rules in this thesis involves a different source of process capability data in the form of graphs, capability curves, etc. Some of these data have been developed throughout the research project. Another part of these data has been collected from company documents and databases, in addition to welding handbooks. These engineering rules have been employed as sources of data in Paper F.

Diary notes: A central method throughout the entire research project has been diary notes. A total collection of 32 diary notebooks has been created. In these notebooks, diary notes were made regarding a variety of phenomena: from interview and observation notes to mental notes, reflections and research design planning, as well as supervisor feedback. These notes have been reviewed throughout the project supporting its progress.

3.2.2 Data analysis methods employed

In the same way as collecting data from different sources has been used as a strength to be able to provide better evidence, data analysis methods have been mixed in use for the same purpose.

To analyze interviews, relevant parts of audio records were listened to and transcribed manually. This analysis format was used because the purpose was not to find word patterns but rather understand complex phenomena related to the welding operation and product design. Therefore, transcribing expert explanations was sufficient. The transcripts together with the interview and observation notes taken in the field were processed by coding. The conceptual framework developed and presented in Paper C (Figure 26) has served the author as a taxonomy or structure with which to code and analyze later interviews.

Notes from interviews, observations, supervision meetings and personal reflections, which were recorded in the Diaries, have been reviewed and color-coded. The purpose was to identify relevant parts and categorize the input.

Manufacturing data and experimental data (extracted from both physical welding and welding simulation experiments) have been analyzed using the statistical software JMP. Different statistical methods have been employed to analyze these data. For example, in Paper B, an Exploratory Data Analysis (EDA) was performed to understand the status of the current inspection data. EDA is an approach to analyze data by employing data visualization methods for the purpose of finding out what data can tell beyond formal modeling (De Mast and Trip, 2007).

Instead, in Paper E, statistical modeling and optimization as well as robustness analyses have been performed using the simulation results table resulting from combining DoE techniques with welding simulation. Contour plots and response surfaces have been plotted to support visualization and analysis of results. Furthermore, in Paper G, parallel coordinates and scatter plots have been employed to visualize and interact with the data in order to study interactions and correlations between parameters.

In general, discussions with experts from industry and academia about the different fields, Design, Welding Simulation and Welding Engineering, as well as DoE experts, have been a central part of the analysis activities. Iterative cycles of analysis and reflection, as the ones described in Action Research, have been performed together with experts in order to develop the research outcome.

3.2.3 Research activities Paper by Paper

Besides the specific types of data collection methods, a more detailed description of the research activities connected to each paper is presented as follows (for a better understanding, see Figure 22 and Table 2):

Paper A: This first paper embraces some of the results obtained during the Master thesis work carried out by the author (Madrid, 2012), including an initial literature review and company study on producibility and Design for Manufacturing. This has allowed the formulation of a preliminary set of RQs and working packages to guide the entire research project. The focus of the literature review has been on methodologies and tools to support designers. Thus, the design process has been the focus area. This paper describes the existing situation both in academia and industry, thus contributing to the field of Design Engineering.

Paper B: The descriptive part of the study presented in Paper B addresses the problem concerning the lack of inspection and manufacturing data usage during design activities. Thus, the focus is placed on both design activity, when the data are used, and the manufacturing and inspection activities, when data are generated. Barriers to the reuse of inspection data have been analyzed and classified by combining the findings from a case study performed at the industrial partner and a literature review. In these research activities, combinations of qualitative and quantitative data and mixed methods have been employed. The case study performed in this paper was part of a Six Sigma project. Thus, methods and tools within the DMAIC framework were employed to analyze the data. Six sigma methods as a research activities have been previously employed by such researchers as Ericson Öberg (2016). Paper B gives a more detailed description of methods used to analyze both quantitative and qualitative data within the Six Sigma framework. In the prescriptive part of this paper, the producibility model, developed in Paper C, is proposed and its usefulness in overcoming some of the barriers is discussed.

Paper C: Paper C focuses on the manufacturing process as study area. It contributes to the description and modeling of product quality creation during the manufacturing process. It is during the manufacturing process that producibility gets tangible, as explained in Chapter 1. The conceptual framework ("producibility model") proposed in this paper has been developed through iterative cycles of literature review, product study and analysis. In each cycle, the model has been adjusted after the analyses were completed in Product I. After the model was finalized, an evaluation study was performed using a different product, Product II. The data governing these studies have been mainly qualitative. Interviews with design and mostly manufacturing engineers have been performed, together with observations of the factory floor and review of internal documents.

Paper D: The literature review in this paper has been used for three purposes: first, to frame the introductory problem; second, to create a frame of reference, including the multidisciplinary design context for aerospace products and a critical review of DFA and DFM methods with respect to welding; third, to develop a design method with which to assess potential welding failures stemming from the design. The method proposed has been developed during iterative cycles of literature review and empirical work on site at the industrial partner. In the final part of Paper D, an evaluation study of the method involving Product II is presented using welding simulations to show the applicability and usefulness of the method. As within Paper C, the study carried out in Paper D combines mixed methods. In this study, results from welding simulations are combined with results from interviews, observations and document reviews in a convergent way.

Paper E: The data employed in this study have been mainly quantitative due to the experimental nature of the study. This is because at this stage, the phenomena of interest could be isolated to design an experimental plan. Even so, informal interviews, observations and company document analyses were carried out in Product III to formulate needs and requirements for the method developed in this paper. Product III has been in a conceptual design phase at the time of the study. Thus, the need for virtual methods to perform producibility analysis was emphasized. Yet, same needs were observed in Product II. From the complex geometry of Product III, a more simplified geometry was designed to perform the experimental and evaluation study. The activities conducted to develop and test the virtual method involved welding experiments to support welding simulation development and the execution of welding simulations. Statistical methods involving Design of Experiments (DoE) techniques were employed to plan simulation experiments and analyze simulation data.

Paper F: The research presented in this paper shares the results of a cross-collaboration between two research projects, the research project governing this thesis and a research project touching upon Platform Design and producibility. First, a literature review was conducted to detect gaps in Platform Design, Design for Manufacturing and Failure Mode and Effect Analysis (FMEA) practices. The result was a definition and categorization of producibility failure modes, which contribute to Descriptive Study I and RQ1. This categorization served to develop a framework to support systematic producibility assessments in Platform Based Design. The methods employed to complete the framework development and validation entailed different types of rule-based models (e.g. engineering rules and trade-off curves) and simulations (path planning and welding simulations). The validation case study was based on Product II.

Paper G: As in Paper F, the research presented in Paper G had the objective of applying the previous results obtained into a real product development environment. In this case, the Multidisciplinary Design and Optimization (MDO) environment at the industrial partner (GKN Aerospace) was selected, which provided this study of a real action research nature. Participatory Action Research cycles have been applied to develop a framework for systematic producibility assessments in MDO environments. These cycles implied discussing, planning, analyzing and reflecting with practitioners based on an empirical study. Product III was chosen for this purpose because it was in a conceptual design phase, which provided a case for real action research. DoE techniques, data obtained from the metamodel developed in Paper E and additional welding simulations conducted by practitioners at the company facilities were employed to develop, test and validate the framework.

3.3 RESEARCH QUALITY CRITERIA

There is a wide consensus that validity and reliability are two central criteria with which to ensure quality in scientific research (Yin, 1994), (Blessing and Chakrabarti, 2009), (Creswell, 2013). In the same way, validation and verification are central activities with which to ensure quality in engineering applications (Maropoulos and Ceglarek, 2010, Sargent, 2010), (Buur, 1990).

Reliability, as the concept for research verification, is concerned with "issues of consistency of measures" (Bryman and Bell, 2015). Reliability relates to the reproducibility of a result, demonstrating that the operations of a study, such as the data collection procedures and experiments, can be repeated obtaining the same results (Yin, 1994). Thus, reliability relates to the question "*Did we do things in the right way?*".

Yin (1994) highlights the importance of documenting the procedures of the cases studies and documenting as many steps as possible as a way of ensuring reliability. Creswell (2013) proposes strategies such as checking transcripts, ensuring no drift in code, crosschecking the codes, to ensure reliability within qualitative method research. In quantitative research, repeatability and reproducibility in both testing and measurement procedures affect the reliability of research outcomes (George et al., 2004). Reproducibility relates to the variation produced when different individuals test or measure the same experiment under the same conditions. Repeatability connects to the variation that occurs when successive experiments are made by the same individual and under the same conditions.

Validity, understood as the concept of results validation, can be seen as the quality of the relationship between the reality and research outcome (Maxwell, 2012). Thus, validity criteria can be considered as trustworthiness, authenticity and credibility, relating to the question "*Did we do the right things?*".

Determining whether or not the findings are accurate from the standpoint of the researcher is a more arduous task when research includes qualitative elements (Creswell, 2013). Therefore, validation activities should occur throughout all steps taken during the research process (Creswell, 2013). Validity as a research quality criterion has been treated in different dimensions. A common classification differentiates between *construct validity, internal validity* and *external validity* (Yin, 1994), (Blessing and Chakrabarti, 2009), (Bryman and Bell, 2015), (Cook et al., 1979).

Construct validity deals with identifying the correct operational measures for the concepts being studied, thereby justifying the importance of giving definitions of the key concepts within the study through conceptualization and operationalization. Construct validity is important to be able to make generalizations about higher order concepts from findings that have been measured (an example of a high order concept is the producibility concept in this thesis).

The concept of internal validity consists of establishing trustworthiness by credibility. Internal validity can be related to the *logical verification* suggested by Buur (1990). These authors claim the need to check a certain degree of consistency, coherence and completeness of the research outcome to be able to verify research in the design field.

Case Study research presents advantages when dealing with internal validity because an in-depth understanding about the phenomena studied can be gained due to the opportunity to immerse oneself into real phenomena (Yin, 1994). In contrast, external validity is a weak point of Case Study research since external validity deals with setting and assuring the generalizability of results (Bryman and Bell, 2015). To overcome this, Yin (1994) proposes using replication logic in multiple-case studies.

Within DRM, the use of the Success and Measureable Criteria can be a way of evaluating whether the research results have a societal impact, a process that strengthens validity (Blessing and Chakrabarti, 2009). The selected Success and Measurable criteria for this thesis is discussed in Subsection 5.3.2.

In addition to the above, other authors have proposed specific strategies for ensuring validity in research with qualitative elements (Maxwell, 2012), (Creswell, 2013), (Yin, 1994). Some of the proposed tactics include, triangulation, expert member checking, explanation building, peer reviews, clarification of the bias, intensive long-term involvement and rich data, to name a few.

Additional methods to test validity in quantitative research can relate to statistical test measures to check the degree of adequacy of, for example, the regression models built (Creswell, 2013, Montgomery, 2017).

In simulation models, operational validation is according to Sargent (2010) defined as "determining that the output behavior of the model has a satisfactory range of accuracy for its intended purpose and on the domain of its intended applicability". Thus, a method to ensure validity can be historical or testing data validation, in which simulation results are compared to physical test results (Sargent, 2010)

The tactics pertinent to this research will be discussed in greater detail at the end of Chapter 5 (see Sections 5.3 and 5.4)

4 Results

This chapter begins with a short summary of the seven appended papers. After the summary, eleven main research results are presented as self-entities derived from single papers or a combination of several papers. Figure 23 illustrates the connection between the eleven main research results (R1-11) and the seven appended papers (Papers A-G).

4.1 SHORT SUMMARY OF THE APPENDED PAPERS

Paper A establishes a framework for the term producibility, discussing why this is the preferred term in the aerospace industry and establishing a soft definition and metrics for the concept of producibility. Producibility can be understood as "the capability to produce a product in a robust and efficient way to meet the design specifications for function and reliability of the product". Quality, time and cost are the effects of producibility and ways in which it may be measured. In addition, in Paper A, a general review of potential methodologies and tools that can be used during Engineering Design to assess producibility is carried out with the objective of finding barriers and gaps with regard to their industrial application and formulating opportunities for future research.

One of the main barriers identified in Paper A is the lack of quantitative data with which to evaluate producibility during the design process. **Paper B** follows up this matter by first highlighting the need for reusing manufacturing data and information to feed probabilistic-based design activities that aim to predict product quality with respect to the manufacturing process. Thereafter, Paper B identified, discussed and proposed a classification of barriers to the reuse of inspection data in design activities. Requirements of measuring and inspecting activities were identified to overcome these barriers. In order to generate adequate producibility information and process capability data that can be used in coming design activities, there is a need to map how quality is built into the product in each step of the fabrication process.

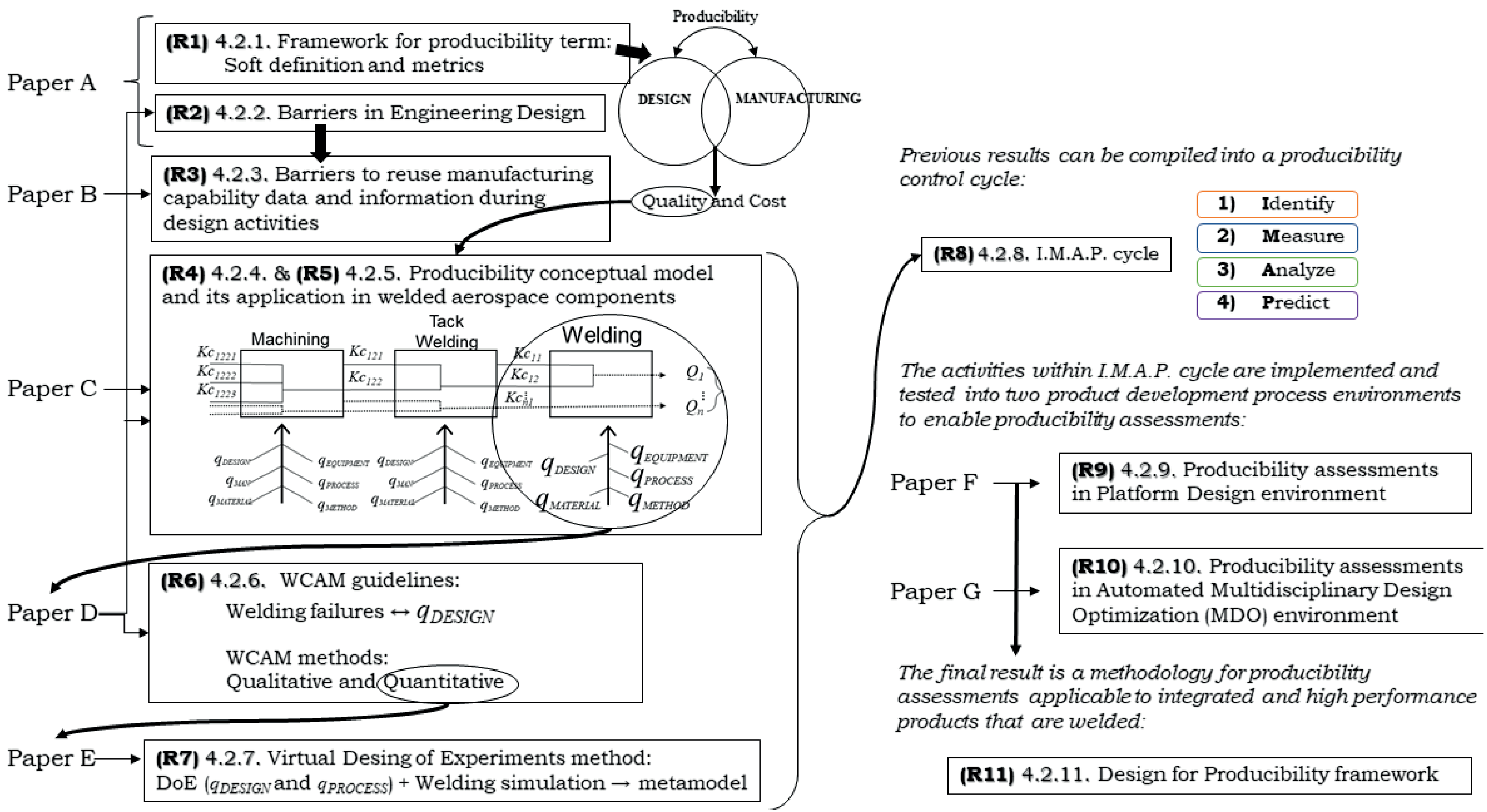

Figure 23 The eleven research results (R1-11) and illustrative connection between all Papers contributions

Paper C, motivated by the barriers identified in Papers A and B, presents a conceptual model to represent product quality creation during the manufacturing process of fabricated aerospace components. As discussed in Paper A, quality and cost are considered to be the effects of producibility. On this basis, and considering quality alone, Paper C presents the producibility conceptual model. In this research, quality is described using the concept of process capability. Thus, quality is defined as the manufacturing output variation in comparison with its tolerance limits. From this definition, the producibility conceptual model has been created combining systems models in the literature. The result is a representation of key product characteristics (KCs) that will eventually deliver quality to the customer (Q) and the parameters or factors (q) which, during the manufacturing of the product, have an impact on the output variation of key product characteristics (KCs). In this representation, each manufacturing operation acts as a delimited system in which inputs, outputs and control factors are represented. This systematic representation helps to visualize all producibility control factors, i.e. factors that affect product quality during the manufacturing process. These producibility factors derive from both the product and manufacturing systems.

The representation provided by the producibility conceptual model works as a foundation for the activities of the producibility control cycle proposed in this thesis (the I.M.A.P. cycle). These activities include*: 1)* ***I****dentify* what affects producibility*, 2)* ***M****easure* what affects producibility*, 3)* ***A****nalyze* the interaction between the factors that affect producibility *and 4)* ***P****redict* producibility. Each paper describes one or several of these activities. In this way, the content of the producibility cycle is implicitly explained throughout Papers B, C, D and E. For example, in the last part of Paper B, the producibility conceptual model from Paper C is proposed to be a core structure of the activity *Measure*.

Paper D describes mainly three I.M.A.P. cycle activities: 1) Identify, 2) Measure and 3) Analyze

Paper D begins by providing a literature review of the DFM and DFA methods in order to justify why the design rules, guidelines and process capability information provided by these methods are not suitable in the case of welded aero structures. Thereafter, Paper D prescribes a method with which to support the generation of new Design for Welding rules and welding capability information. The proposed Welding Capability Assessment Method (WCAM) is a compilation of different tools with which to perform a systematic identification and analysis of design parameters related to product geometry critical to the welding process. Within this method, a guideline connecting potential welding failure modes to specific design parameters is created to support the identification of critical design parameters (producibility control factor labelled as q_{DESIGN} in the producibility conceptual model presented in Paper C). In a following step, quantitative methods are proposed to analyze the bandwidths with which to fulfill manufacturing quality and calculate tolerances on those design parameters in order to reduce the likelihood of welding failures, thus ensuring weld quality. From the method, qualitative and quantitative information about the welding capability can be generated to support design decisions.

Paper E describes mainly two I.M.A.P. cycle activities: 3) Analyze and 4) Predict

Paper E follows a further investigation on how to systematically generate welding capability data and information of a quantitative nature. The main contribution behind Paper E is a step-based approach that combines the benefits of Design of Experiment (DoE) techniques with the benefits of welding simulation. The objective is to model and optimize the effect of design and welding parameters (q_{DESIGN} and $q_{PROCESS}$) interactions on the weld quality of the final product (defined by KCs). Virtual Design of Experiments enables an experimental design with minimal runs at the same time as these runs can be simulated in shorter time if compared to physical testing. The response surface-based metamodel obtained from the regression analysis made from the virtual DoE study allows three type of analyses: 1) Identification of unfeasible regions in the design-manufacturing space (i.e. regions within which the design-manufacturing variants do not fulfill producibility requirements); 2) Optimization of design and welding parameters and 3) Robustness analysis.

In addition, the metamodel built, representing the welding capability space, works as a predictor that can be employed to assess the producibility of future design concepts.

The next two papers, Papers F and G, consider the comprehensive set of results from previous papers compiled into the producibility control cycle (I.M.A.P. cycle) in order to implement and test it in the global framework of the product development process. The objective is to develop and validate a framework for product development that enables a systematic approach to perform producibility assessments for highly integrated performance products that are welded within a Multidisciplinary Design context.

The ultimate aim is to equip the producibility stakeholder in a multidisciplinary context with the same tools and approaches as exist within the fields of Mechanical Engineering and Computational Fluidynamics in order to achieve similar levels of automated and virtual analysis.

Two different multidisciplinary product development environments have been selected to validate the set of results. The first environment is: 1) Platform Design (covered in Paper F). The second is: 2) a Multidisciplinary Design Optimization (MDO) environment (covered in Paper G). Both environments are based on the principles of Set-Based Concurrent Engineering.

Paper F focuses the discussion on the industrial product development context of 1) Platform Design. The results presented in this paper involve the modeling, configuration and producibility assessment of product-manufacturing variants on the basis of platform modeling. The aim is to generate a large number of product-manufacturing variants and simultaneously and systematically assess their producibility adopting Set-Based principles in the context of Platform Design. To do so, first, an integrated platform approach is applied to model variety. Thereafter, producibility assessments are divided in two consecutive stages, Rapid and Precise, depending on the level of information and fidelity of the product-production concepts. At each of these stages, screening of variants is performed based on two types of producibility failures, defined in the paper as operational and quality producibility failures. The former inhibits the welding operation from being executed. The latter causes detriment in output weld quality. The two-stage assessment approach based on two levels of screening prescribes a structured and systematic way in which to virtually assess the variants generated by the integrated platform model and systematically eliminate the unfeasible ones.

Paper G focuses on the industrial product development context of 2) an automated Multidisciplinary Design Optimization (MDO) environment. This paper describes how to perform producibility analysis and trade-off against the analysis results from the remaining performance disciplines in an industrial case scenario. Previously built welding capability information, such as the metamodel presented in Paper E, is employed to constrain the design space generation as well as to predict weld quality output of all design variants generated. The metamodel is used to analyze the quality of the weld bead, in particular the assessment of joint penetration. In addition, welding simulations are performed on all design variants to provide results in the area of geometrical variation (distortion), thus completing the producibility assessment. Thereafter, design variants are analyzed in terms of cost, weight and stiffness. To complete the multidisciplinary analysis, an interactive tool based on parallel coordinate diagrams is applied to help visualize and evaluate the trade-off of all disciplines, including producibility.

The output of these studies is the Design for Producibility framework, which prescribes how to model the fabrication process and map contributors to manufacturing variation, as well as provides support to the activities of identification, measurement, analysis and prediction of producibility. The framework prescribes how to conduct these activities in a systematic way within a multidisciplinary design context while obeying set-based principles.

4.2 BODY OF RESULTS

The key findings of this thesis are presented in this section as eleven main research results: see (R1-11) in Figure 23. Each subsection corresponds to a main research result. The number of each subsection is also indicated in Figure 23 accompanying the main research result. The objective is for the reader to easily select those findings of greatest interest.

4.2.1 (R1)—Framework for producibility term: soft definition and metrics—Paper A

In the first part of the study covered in Paper A, a large number of definitions of producibility and manufacturability found in literature were reviewed and differences among both terms were discussed with regard to their application. Figure 24 attempts to illustrate the distinction between these terms. In producibility, there is a strong link to product functions, characteristics and performance. In contrast, within traditional manufacturability or Design For Manufacturability (DFM), the product function and its characteristics are of less concern and production optimization is instead the focus. The reason is that, for manufacturability, the common applications include products that can be complex in the number of parts without geometry and product characteristics being highly linked to product functionality. Thus, a change regarding product structure or form to optimize production will not affect product performance, which is not the case for integrated aerospace structures. In addition, the common manufacturing process technologies used as application examples feature high levels of maturity and repeatability, which is not the case for some welding and advanced material technologies used in aerospace. For these reasons, the producibility term is preferred in the case of aerospace applications.

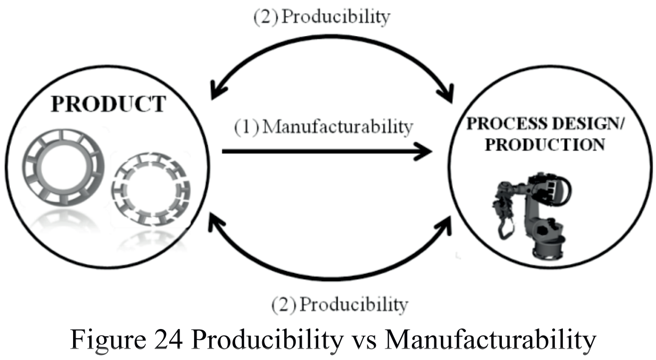

Figure 24 Producibility vs Manufacturability

Furthermore, to provide a complete framework for the term producibility, a soft definition together with metrics to evaluate producibility is given in this paper. Producibility can be understood as "*the capability to produce a product in a robust and efficient way to meet the design specifications for function and reliability of the product* ".

The metrics selected to measure the producibility concept are:

- Quality – process capability. The simulation or estimation of the process output (6σ) in comparison to the product requirements (tolerance limits) at each process step.
- Time – (total) process time. The total of time needed for each process step to fulfill all product quality requirements and specifications.
- Cost – (total) process cost. Refers to the total of manufacturing cost necessary for each process step to achieve product quality requirements. Cost can be calculated from the

planned operation sequence, including special tooling.

Due to the strong relation between cost and time, producibility can be conceptualized by using the Quality and Cost metrics. This definition and the two metrics create the starting point for the rest of the research presented in this thesis.

4.2.2 (R2)—Barriers to addressing producibility in Engineering Design—Papers A and D, additional contributions from Papers E, F and G

In the second part of the study presented in Paper A, a literature review was made within the field of Engineering Design to identify and analyze potential methodologies and tools that might be beneficial to apply in order to consider producibility aspects during the design development process. The methodologies and methods that have been analyzed with the objective of finding barriers and gaps in industrial application are presented in Table 3. In addition, a deeper study of DFM and DFA methods have been performed in the first part of Paper D.

Furthermore, as the research project progressed, additional insights about the gaps and barriers to performing producibility analysis during the multidisciplinary design process have been gained during the most recent studies presented in Papers E, F and G.

Table 3 Methodologies and methods in Engineering Design chosen for analysis

Methodologies in Engineering Design	Methods in Engineering Design
• Integrated product development (IPD) • Concurrent Engineering (CE) • Systems Engineering (SE) • Set Based Concurrent Engineering (SBCE)	• Quality Function Deployment (QFD) • Failure Mode and Effect Analysis (FMEA) • Fault Tree Analysis (FTA) • PUGH matrix • Design for “X” tools • Design for Manufacturing and/or Assembly (DFM/DFA) tools • Robust Design tools • Design of Experiments (DoE)

Highlights and conclusions from the results obtained in Papers A and D and the insights gained through the studies performed in Papers E-G can be summarized as follows:

Within the multidisciplinary design process of aerospace components, advancements in computer technology and software allow the automated analysis of a large number of design variants from the perspective of mechanical engineering and aerodynamics disciplines. In theory, within this product development context, the use of SE and SBCE is convenient to set and verify requirements. These methodologies enable the building of knowledge and facts about a variety of design concepts before decisions are made. This characteristic is especially important in the case of novel and non-mature technologies, such as the advanced materials and welding methods employed in aerospace applications. However, producibility as a criterion and manufacturing as a stakeholder have still not been fully considered within these methodologies. The assessment of producibility and manufacturing capabilities based on CAD geometry is, if possible, mostly limited to the interactive and manual analysis of a single design.

The DFM and DFA methods can be useful to some extent. However, they are of limited use to material and processes employed in aerospace welded components. In addition, these methods lack quantitative targets and analyses with which to evaluate and secure manufacturing quality. Hence, Robust Design (including welding simulation) and DoE methods can point the way forward.

In industry, in the particular case of welding, process capabilities are physically tested for those phenomena that welding simulation cannot cover. However, laboratory tests are planned for single cases. Thus, no support is provided on how the different product geometries, constituting the design space, affect the output of the welding process. Efforts are mainly directed at finding the welding process parameter window for a single design concept. In literature, studies can be found that employ DoE and other statistical and numerical approaches to predict and optimize weld quality for different welding methods. However, including a variety of design parameters with which to study the interaction with product design is less explored. In addition, only a few studies combine DoE with welding simulation.

Therefore, the complexity of the welding process and lack of virtual support make the understanding of causes and effects during design space analysis, i.e. the early phases of product development of aerospace components, still reliant on expert judgements.

In summary, the implementation of the methodologies and methods reviewed (see Table 3) can be hampered due to the following barriers:

1. The lack of producibility criteria for use in design evaluations.
2. The subjective nature of existing information about producibility based on expert opinions.
3. The lack of guidelines including know-how and structured expert knowledge for new and advanced materials and welding technologies.
4. The lack of welding capability knowledge and quantitative data with which to perform optimization and evaluate trade-off alternatives between producibility and other disciplines during multidisciplinary design analysis.
5. The lack of quantitative methods with which to evaluate producibility.
6. The lack of virtual tools (lack of predictive models and incomplete simulation).

From the previous analysis, three clear requirements were identified to mark the direction of this research project and help establishing the research questions:

- The need to clearly understand what contributes to producibility and how to measure it.
- The need to develop additional methods and tools to help measure and evaluate producibility.
- The need for virtual tools to perform producibility evaluation within multidisciplinary design analysis.
- The need to implement a framework during the product realization process that would integrate all methods and tools necessary to evaluate the producibility of a large set of design variants in a systematic way, i.e. according to SBCE principles.

4.2.3 (R3)—Barriers to reuse manufacturing capability data and information to support Robust Design activities—Paper B

One of the barriers, identified in Paper A, when applying methodologies and methods to ensure producibility during the design process in the aerospace industry is the lack of quantitative data, i.e. the lack of capability data for some new materials and manufacturing processes. Paper B considers this matter further. First, Paper B highlights the need for reusing manufacturing process capability data and information to feed Probabilistic-Based design activities that aim to predict product quality with respect to the manufacturing process. Much of these approaches assume the existence of process capability data. However, in industry, inspection data, one of the main sources of process capability data, are mostly employed to optimize production. Thus, Paper B presents two questions with which to guide the study:

Paper C Q1: What are the barriers to reusing inspection data during robust design activities?
–That is: If we measure during inspection activities, why are we not reusing that data?

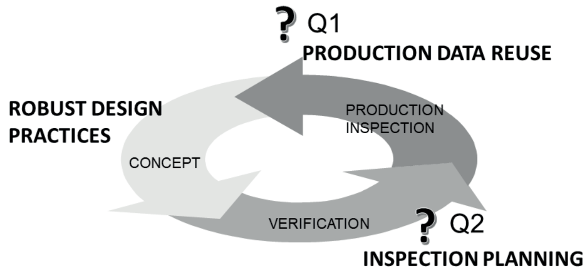

Figure 25 Case study questions allocated within the geometry assurance cycle

Paper C Q2: What are the requirements and needs on inspection planning and measurement activities in order to generate adequate process capability data to utilize during probabilistic-based design activities?

To address the first question, a classification of barriers to reuse inspection data into design activities is proposed. Specific barriers extracted from a case study at the aerospace industrial partner were compared to generic barriers found in literature. The barriers were then classified into information[1], technical and organizational barriers (See Table 4).

Table 4 Classification of barriers to reuse inspection data during Robust Design activities

Type		Generic Barriers (Literature study)	Specific Barriers (Case study)
Information nature	*Why*	Designers and other stakeholders are uncomtemplated as possible users of measurement data	Fatigue life calculation is not considered as user of inspection data
	What	What need to be measured, product characteristics, process parameters or material data, is not identified	Poor weld defect characterization
	How	How to measure, metrics, and how to present the data, need to be defined	Inspection operators are not trained on how to generate data for fatigue life calculation purposes
	When	Lack of planning when to measure leads to poor population and out of date data	Weld defects are only inspected after the complete welding of the final assembly
Technical nature		Inadequate data management-systems. Incompatibility between different systems	The design of the data management-system induces subjectivism. Two different reporting systems
		Untrusted data. Deficient MSA	The inspection data is operator dependent
		Deficient inspection equipment	Capabilities of NDT methods are not optimized
Organizational nature		Poor comunication between design and manufacturing	Lack of cross functional communication between inspection and fatigue life calculation departments
		Lack of management support to invest in resources such as equipment, data maintenance and training	Lack of standard inspection procedures

[1] Please note that the term "informational barrier", as it appears in Paper C, has here been substituted for "information barrier" because the latter is more accurate in meaning. Information barriers relate to the information provided by the data to be utilized during design and the adequacy of these data for design analysis.

Information barriers relate to the quality of data content, i.e. how pertinent and adequate are data generated by the inspection process to support robust design activities. *—do inspection data contain the adequate information to support design activities?*

Barriers technical in nature are connected to the quality of the inspection, measurement and data management systems. Barriers of organizational nature relate to the collaborative interaction between design and manufacturing.

Even so, these three types of barriers are interconnected, e.g. the quality of the measuring system implicitly affects the quality of the data content.

After presenting this classification, Paper C elaborates further on information barriers. The study focuses then on understanding the reasons why data generated do not contain adequate information. From the analysis of these reasons, requirements on inspection and measurement activities can be set.

The reasons why inspection and measurement processes do not generate adequate data content are first because the measurement purpose has not been clearly defined (*Why to measure*). In many cases, the activities to assure manufacturing quality during design stages (e.g. variation and welding simulation) have not been identified as potential users of inspection data. Still, production optimization and repair activities are the predominant stakeholders of these data.

In second place, *What to measure* defining the quality of the product has not been properly identified. The key product characteristics linked to product functionality, and the process parameters causing variation of those key product characteristics, have not been properly identified as measurement features. In addition, *How to measure* also needs to be planned by identifying the metrics by which those product characteristics and process parameters can be verified during the product development process. Finally, planning *When* in the process to measure is necessary in order to either capture the phenomena that simulations aim to model during design stages or to perform root cause analysis during production. Requirements of *When* to measure are also important to overcome the barrier of poor population and out-of-date data.

Therefore, there are requirements placed on the inspection planning activity that need to be fulfilled in order to clarify *Why*, *What*, *How* and *When* to measure so that data with adequate quality content can be generated. First, there is a need to implement a Quality Assurance cycle to identify new users of inspection data throughout the product realization process and pull the required information. Second, there is a need to model and map the manufacturing process so that top level user requirements are broken down into measurement requirements at each step of the manufacturing process. A producibility and variation propagation model would help structuring the connections with which to identify the causes of variation and how variation propagates through the product system along the different steps of the manufacturing process, defining *why*, *what*, *how* and *when* to measure.

4.2.4 (R4)—Producibility conceptual model for welded and highly integrated performance components—Paper C

Paper A has studied the barriers for addressing producibility in Engineering Design. One of the main barriers is the lack of quantitative data with which to evaluate producibility. A follow-up study, in Paper B, has revealed that the reason why there is a the lack of manufacturing process data to be utilized during Robust Design activities, connects to the lack of a core model to identify what defines and affects producibility. Thus, there is a need to state what, how and when needs to be measured in the manufacturing process. Therefore, whereas Paper A and partly Paper B look at the problems when addressing producibility during the design process, Paper C focuses on the manufacturing process.

As clarified in the Introduction, producibility is a property that gets tangible during manufacturing. It is during the manufacturing process that producibility problems arise. Therefore, the study of phenomena that occur during manufacturing operations is required to understand what contributes, affects and thus defines producibility.

Producibility has been conceptualized in Paper A using the quality and cost concepts. Paper C takes into consideration the quality dimension alone and aims at creating a model that represents product quality creation during the manufacturing process of fabricated components (see Figure 26).

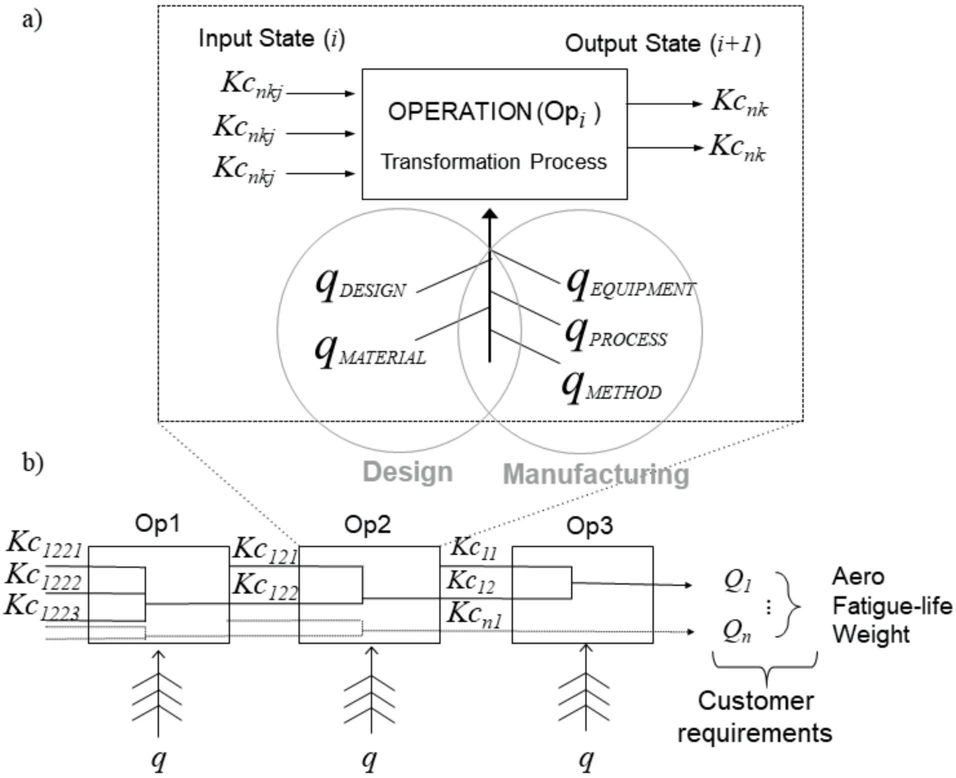

Figure 26 Producibility model: conceptual framework to represent product quality creation during the fabrication process

Quality is defined as the manufacturing output variation in comparison with the tolerance limits, as in the Quality Engineering Theory (Taguchi et al., 2005).

Thus, quality can only be defined when the product and manufacturing systems intersect. This interaction is represent by the circles interacting in Figure 26. From the definition of quality, a conceptual model has been created by combining systems models found in existing literature. The areas of manufacturing process modeling and variation propagation modeling have been reviewed. Both areas represent systems modeling with one being more focused on the manufacturing process and the other on the product. Thus, the combination of both makes it convenient to capture producibility phenomena.

First, Figure 26 a) represents how quality is built into a specific manufacturing operation. In this model, the operation is considered a transformation system, inspired from the Theory of Technical Systems (TTS). TTS by Hubka and Eder (1988) describes how the manufacturing equipment acts as a technical system (TS) which executes the transformation process (TrfP) or physical transformation that occurs to a product during a manufacturing operation. The workpiece undergoing the manufacturing operation can be considered an operand (Od) transformed from an input state (Od_1:raw material) into a desired output state (Od_2: final product geometry). In the same way, the model presented in Paper C (Figure 26 a)) describes the transformation of key characteristics (KCs), i.e., the product characteristics critical to the function and performance quality of the product (Thornton, 2004).

Figure 26 b) represents how quality is built during the sequence of manufacturing operations in which KCs act as operands being created and transformed until the final operation has been reached. By then, the product ought to contain the product characteristics, features and properties that carry the performance and quality with which to fulfill the technical needs and requirements of the customer (Qs). The *Q-quality* concept was adopted from (Mørup, 1993). Qs represent the final product quality connected to customer requirments. KCs represent the internal product quality, ie. product quality at the different product system levels. The sequence of KCs is made so that inputs and outputs of each operation (Op_i) can represent variation propagation.

The transformation of KCs can be controlled by factors related to both the product and manufacturing systems, which in their interactions influence the variation of the outcome of the operation. To represent these producibility control factors acting as sources of variation, an Ishikawa diagram developed by Söderberg et al. (2006b) was adopted in the model. The denotation of producibility control factors is inspired by the *q-quality* concept developed by Mørup (1993). The producibility control factors q_{DESIGN} and $q_{MATERIAL}$ refer to the product geometry and material characteristics selected by designers and thus belong to the product system. The other producibility control factors, q_{METHOD}, $q_{EQUIPMENT}$ and $q_{PROCESS}$, relate to the manufacturing system as they refer to manufacturing equipment aspects, manufacturing process variables (welding current, voltage or speed) and process methods including welding and fixturing sequences.

The producibility conceptual model developed in Paper C represents a structure or a taxonomy with which to plan what to measure to obtain the correct data content and information. With this model at hand, data can be gathered to track variation and thus quality creation. However, the model itself is just a representation of *what* needs to be measured, *why* and *when*. The model aims to classify and represent the different factors affecting the product quality creation during the sequence of manufacturing operations. However, the model itself does not address *how* to identify and analyze those producibility control factors. There is a need for additional tools and methods with which to address identification, analysis and prediction. Results (R6 and R7) connected to Papers D and E contribute to this matter.

4.2.5 (R5)—Producibility conceptual model applied to welded aero components—Papers C and D

The producibility conceptual model in Figure 26 is presented in a generic form to support generalizability. In this way, the model can be extrapolated to any application that shares similarities with assembled and high performance products that undergoing producibility issues. Even so, the producibility conceptual model has been originated, developed and applied to integrated aerospace welded components throughout the thesis. Therefore, in this subsection an illustrative example of the application of the model in welded aerospace components (Figure 27) is provided since it is considered a main contribution to both the industrial and academic fields.

The example given in Figure 27 is based on two parts that intend to be welded for a generic aerospace application. The producibility conceptual model has been applied to these two parts to conceptually represent how performance quality is built into each manufacturing operation.

The generic bill of operations of welded aerospace components proposed in this thesis is composed of four principal manufacturing operations: Op1) Forming processes, such as casting, forging, sheet metal forming and additive manufacturing, are employed to produce part shapes that will later be assembled into the whole product. Op2) Machining with Computer Numerical Control (CNC) machines is employed to prepare the condition of the weld interface surfaces to be welded. Op3) Tack welding are spot welds used as a temporary means to hold parts a proper distance apart (gap) and alignment (flush). This operation together with machining constitute the joint preparation group. Op4) Robot welding is the main joining technique employed to fuse parts to produce a continuous weld. In addition to these four operations, it is worth noting that fixturing, as the act of placing the parts in a fixture to be locked and aligned in optimal position, takes place before the execution of any of these operations. Thus, the design of the fixturing points (see locating schemes in Figure 27) also acts as a source of variation, i.e. as a producibility control factor (q_{DESIGN}).

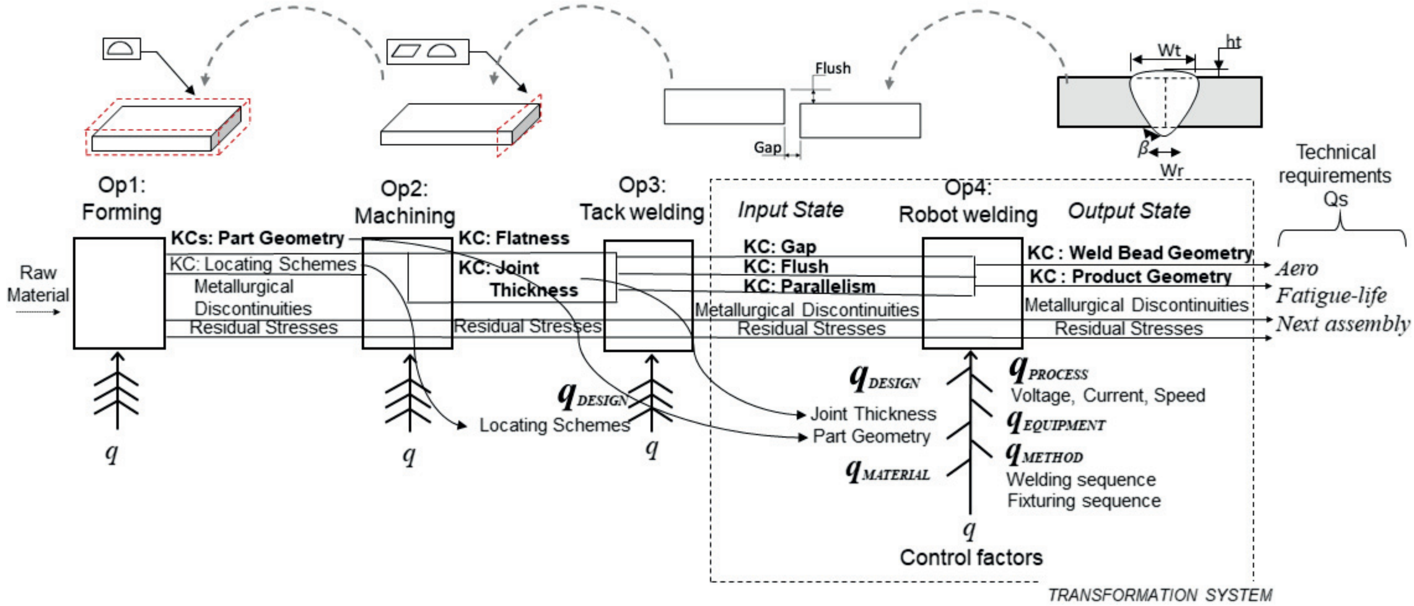

Figure 27 Illustrative example of producibility model used for aerospace application

The chain of these operations transforms the product from raw material to the final state. In the final state, i.e. after the welding operation, the final product consists of certain key product characteristics (KCs) that constitute the properties necessary to fulfill functional and performance requirements, such as aerodynamics, fatigue life and next assembly level performance (Q-quality).

For the identification of KCs, the KC-flowdown from Variation Risk Management (Thornton, 2004) together with calculation methods (see Table 5), are employed to break down top-level product functional or performance requirements (Qs) into technical requirements at each product subsystem level, thus generating requirements at each assembly level. In this way, key characteristics (KCs) can be identified as inputs and outputs of each operation.

In the case of welded aircraft components, the key product characteristics (KCs) output of a welding operation that affect product functionality (Qs: product life, aerodynamics and next assembly performance) include:

1. Weld bead geometry
2. Metallurgical weld discontinuities
3. Critical form dimension (product geometry)
4. Residual stresses

Different calculation methods can be employed to set target values and tolerances in the output KCs to fulfill technical requirements and ensure adequate performance of welded aircraft structures (see Table 5).

Table 5 Calculation methods to set tolerance limits in output KCs (updated from Paper D)

Identified output KC	Connection to performance (*big Q*-Quality)	Calculation method for setting tolerances	Limits
1) Weld bead geometry	Fatigue life	Crack propagation calculation method (ex. Paris´ law)	KC1 + T
	Aerodynamics	Computational Fluid Dynamics (CFD)	KC2 + T
2) Metallurgical discontinutites	Fatigue life	Crack propagation calculation method (ex. Paris´ law)	KC3 + T
3) Form dimensions (product geometry)	Fatigue life	Structural finite element analysis	KC4 + T
	Aerodynamics	Computational Fluid Dynamics (CFD)	KC5 + T
	Performance of the next assembly	Variation and welding simulation	KC6 + T
4) Residual stresses	Fatigue life	Structural finite element analysis	KC7 + T
	Performance of the next assembly	Variation and welding simulation	KC8 + T

1) The weld bead geometry is described by certain parameters or KCs (Wt, Wr, β, ht) that define weld bead quality (see Figure 27). The dimensions of a weld bead can affect aerodynamics and product life. For example, the weld bead height (KC: ht) can work as a step in the air flow. Sharp edges can concentrate a lot of tension which affects the mechanical properties. Thus, the exact dimension and tolerances of the weld bead needs to be calculated.

2) Metallurgical weld discontinuities, such as cracks and pores, are natural effects of the welding process. If these defects grow due to exposure to cycling loading, they can lead to product failure due to fatigue. The limits of these defects regarding number, size and location are determined by crack propagation calculation methods.

3) Geometrical variation in product geometry (form dimensions) can affect the stress distribution, affecting the fatigue life of the product, as well as the aerodynamics. Tolerances can be set from structural and fluid dynamic calculations. In addition, the edges that will conform to the joint in the next assembly require special form tolerances. Due to variation stack-up, it is important to ensure alignment conditions (gap, flush, parallelism) for the performance of the next welding operation. Variation simulations are employed to estimate the output result and set tolerances.

4) Residual stresses can affect product life as well as performance of the next assembly level. Research has shown that it is important to consider the accumulation of residual stresses when simulating distortion due to welding (Steffenburg-Nordenström and Svensson, 2017).

The KC flowdown applied in the producibility conceptual model involves decomposing the final KCs into KCs at each of the previous operations (see Figure27). For example, the geometry of the weld bead is described by certain parameters or KCs (Wt, Wr, β, ht) and tolerances. Considering the welding operation as a transformation system, the welding outcome depends on the input state of the KCs, which is the result of previous operations. Therefore, weld bead geometry is influenced by the output KCs of the tack welding operation, in which proper alignment conditions for the parts to be welded (represented by the gap, flush and parallelism KCs) must be guaranteed. During machining operation (CNC), the KC flatness of the surfaces to be welded and form tolerances of KC joint thickness need to be assured to deliver proper weld alignment conditions while tacking. Ultimately, the KCs defining the part geometry quality given by the net shape forming process will affect flatness and thickness quality.

Some of the KCs created during previous operations (such as part geometry and joint thickness, as indicated in the example of Figure 27), although being design parameters, can act as producibility control factors (q_{DESIGN}) to the robot welding operation system. For example, part thickness (q_{DESIGN}) in combination with the type of equipment and welding method (q_{METHOD} and $q_{EQUIPMENT}$) will determine the amount of heat to weld, which eventually will influence weld bead geometry. During tack welding, the design of the locating schemes will affect the quality of the alignment, thus affecting gap and flush KCs.

In general, (q_{DESIGN}) and ($q_{MATERIAL}$) refer to design parameters, as well as material types and their composition, chosen by designers. Thus, these producibility control factors derive from the product system. The other producibility control factors, ($q_{PROCESS}$), ($q_{EQUIPMENT}$) and (q_{METHOD}), relate to the manufacturing system as they refer to manufacturing process variables (welding current, voltage or speed), manufacturing equipment aspects (robot type) and process methods (e.g. welding or fixturing sequences), which can also be controlled and optimized to improve output quality.

The identification of all KCs and producibility control factors within the producibility model creates an information framework related to the quality control of welded structures. However, *How* to analyze, control and predict quality is prescribed in the coming Papers D and E, in which expert knowledge, in combination with simulation and experimentation, is utilized.

4.2.6 (R6)—Welding Capability Assessment Method (WCAM): Identification and Analysis—Paper D

In order to support the activities of identification and analysis of the KCs and producibility control factors represented in the producibility model, Paper D presents the Welding Capability Assessment Method (WCAM), see Figure 28.

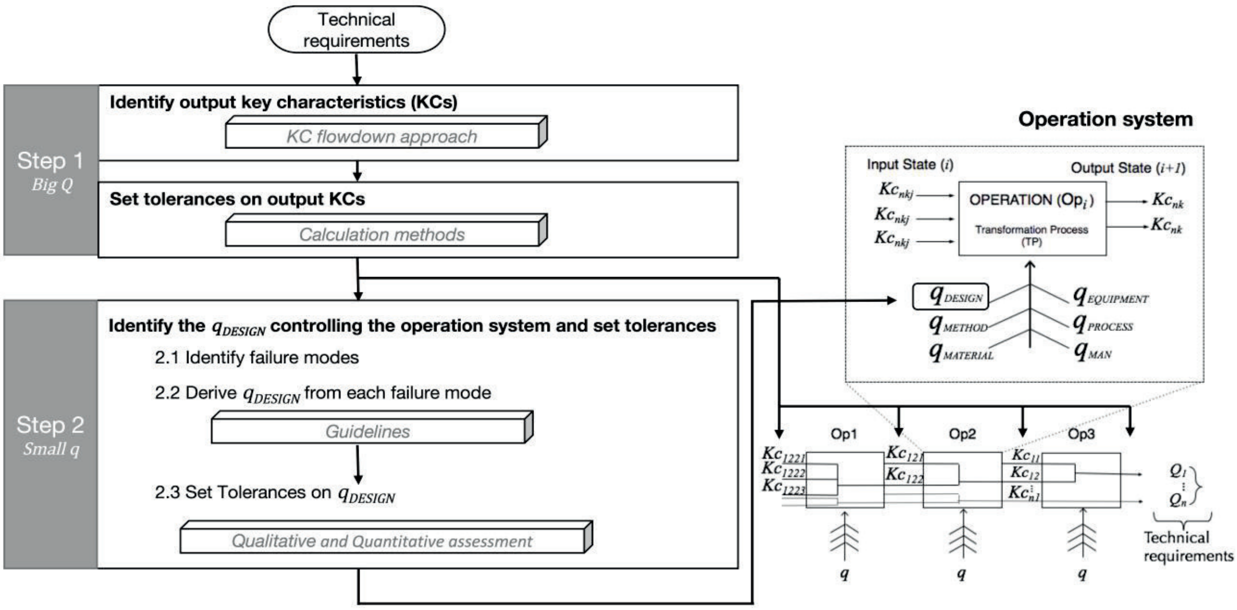

Figure 28 WCAM method: steps and tools

This method focuses on producibility control factors that relate to design parameters, which affect the product quality resulting from the welding operation. The method aim is to identify input and output KCs and producibility control factors (q_{DESIGN}) in the welding operation system and propose ways to analyze the relation between them.

The Welding Capability Assessment Method (WCAM) entails two mains steps, outlined in Figure 28. Step 1 basically involves the identification of KCs employing the KC flowdown approach (see Subsection 2.2.6.1) and the calculation of tolerances as explained in Subsection 4.2.5.

In Step 2, the objective is to identify the product design parameters (q_{DESIGN}) that cause variation on the output KCs of the welding system identified in Step 1. The ultimate objective is to find relationships (sensitivity coefficients) between producibility control factors (q_{DESIGN}) and output KCs. To conduct Step 2, the WCAM prescribes three sub-steps outlined in Table 6.

Table 6 Step 2 in Welding Capability Assessment Method: WCAM guidelines

Step 2.1	**Step 2.2**	**Step 2.3**			
		Qualitative analysis	**Quantitative analysis**		
Failure mode	q_{DESIGN}	*(Higher probability of failure if q_{DESIGN}...)*	Standards Handbook	Physical test	Simulation test
Incomplete joint penetration	*Thickness (t)*	Increases	Yes	Yes	No
Incomplete joint penetration	*Thickness uniformity (u_t)*	Increases	No	Yes**	No
Underfill & excessive reinforcement root side					
Overlap root side	*Inner radius (r)*	Decreases	No	Yes**	CAD model offset
Limited accessibility to inspect					Path planning simulation
Limited accessibility to weld (limited robot rotation)	*Outer radius (R)*	Decreases	No	Yes**	Path planning simulation
Incomplete joint penetration					Authors´ proposition *
Overlap top side					
Distortion (Multiple weld passes)					Welding simulation
Limited accessibility to inspect	*Width (w)*	Decreases	No	Yes	Path planning simulation
Limited accessibility to weld	*Distance (H)*	Decreases	No	Yes	Path planning simulation
Weld bead geometry issues and metallurgical discontinuities				Yes	No
Distortion	*Distance(H) Length (l) Inclination (θ)*	Increases	No	Yes**	Welding simulation

The first two columns in Table 6 work as a guideline with which to identify failure modes and connect them to specific design parameters (q_{DESIGN}). The list of design parameters and the connection to failure modes has been named as WCAM guidelines in this thesis.

Once the identification of critical design parameters (q_{DESIGN}) have been made, the objective is to analyze how these design parameters affect welding output KCs, thus weld quality.

The ultimate aim is to support tolerance settings on the design parameters identified (q_{DESIGN}) in order to guarantee a successful welding operation. The WCAM method proposes the combination of two type of analyses, qualitative and quantitative.

Knowledge of previous welding experiences, as well as technical know-how have been gathered and structured within the WCAM guidelines to support qualitative analyses. The WCAM guidelines can provide a first understanding of the relationship between (q_{DESIGN}) and failure modes. For example, for each of the (q_{DESIGN}) extracted, the WCAM guidelines (Table 6) indicate a higher possibility of failure if the nominal value of (q_{DESIGN}) increases or decreases.

This qualitative analysis serves as a first-glance guide to evaluate the impact of design on welding outcomes. However, this estimate needs to be complemented by quantitative analysis to provide a more accurate evaluation supporting the tolerance setting process. Thus, on the right side of Table 6, methods for quantitative analysis are presented.

In Paper D, an industrial case study was introduced in which combinations of interviews and welding simulations were used to evaluate the effect of two design parameters (q_{DESIGN}: radius and thickness) into the KC weld bead geometry-overlap. The results are presented in Figure 29, which can be employed to understand the capability limits of the welding technology employed in this type of product geometry, information that can be reused in future projects.

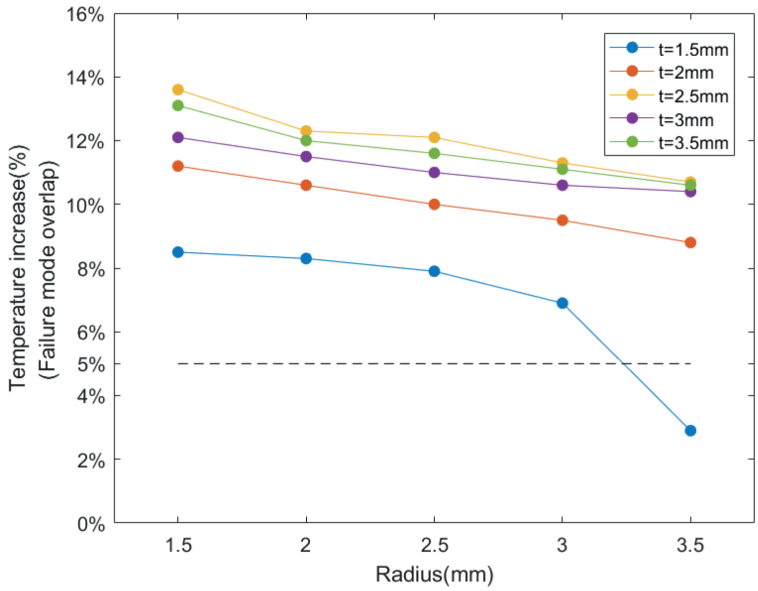

Figure 29 Capability graph—relationship between the design parameters (radius and thickness) and temperature increase (failure mode overlap-connected to weld bead geometry)

4.2.7 (R7)—Virtual Design of Experiments: Analysis and Prediction—Paper E

Paper E follows a further investigation of how to systematically generate welding capability data and information of a quantitative nature.

In the previous study, Paper D considers only design parameters (q_{DESIGN}). However, design parameters (q_{DESIGN}) are not the only producibility control factors, as shown in the Ishikawa diagram within the producibility model. Thus, Paper E runs an investigation to study the effect of both design (q_{DESIGN}) and welding process parameters ($q_{PROCESS}$) on weld quality.

One of the main contributions behind Paper E is a step-based approach that combines the benefits of Design of Experiment (DoE) techniques with the benefits of welding simulation (see Figure 30). This systematic approach enables the rapid building of a metamodel during design stages to analyze, control and predict the individual and interacting effects of design and welding parameters on the final product weld quality.

The investigation and the steps of the approach carried out in Paper E are illustrated in Figure 30. Images of the main results from each step are placed on the right hand side of Figure 30.

In Paper E, the Virtual Design of Experiments method has been applied to an industrial case study. A total of four design and process parameters have been considered in order to study their effect on joint penetration and geometrical deformation (distortion). One of them is the laser beam incident angle.

Welding simulation needed to be developed to consider the effect of the laser beam incident angle. In order to develop the welding simulation, physical experiments were conducted performing different welds varying the bean incident angle. From these data, a new combined heat source model was proposed to simulate the effect of tilting the beam angle.

Once the welding simulation was ready, the first step in the Virtual Design of Experiment block (Block 3) involved applying the DoE technique optimal design that allows the simultaneous consideration of design and process parameters (q_{DESIGN} and $q_{PROCESS}$). The result of applying this technique was a matrix with only a few number of experiments in order to model the effects. The experiments dictated in the matrix were conducted with welding simulation. The table with simulation results was then imported into the statistical software to model the response function, in this way obtaining a metamodel.

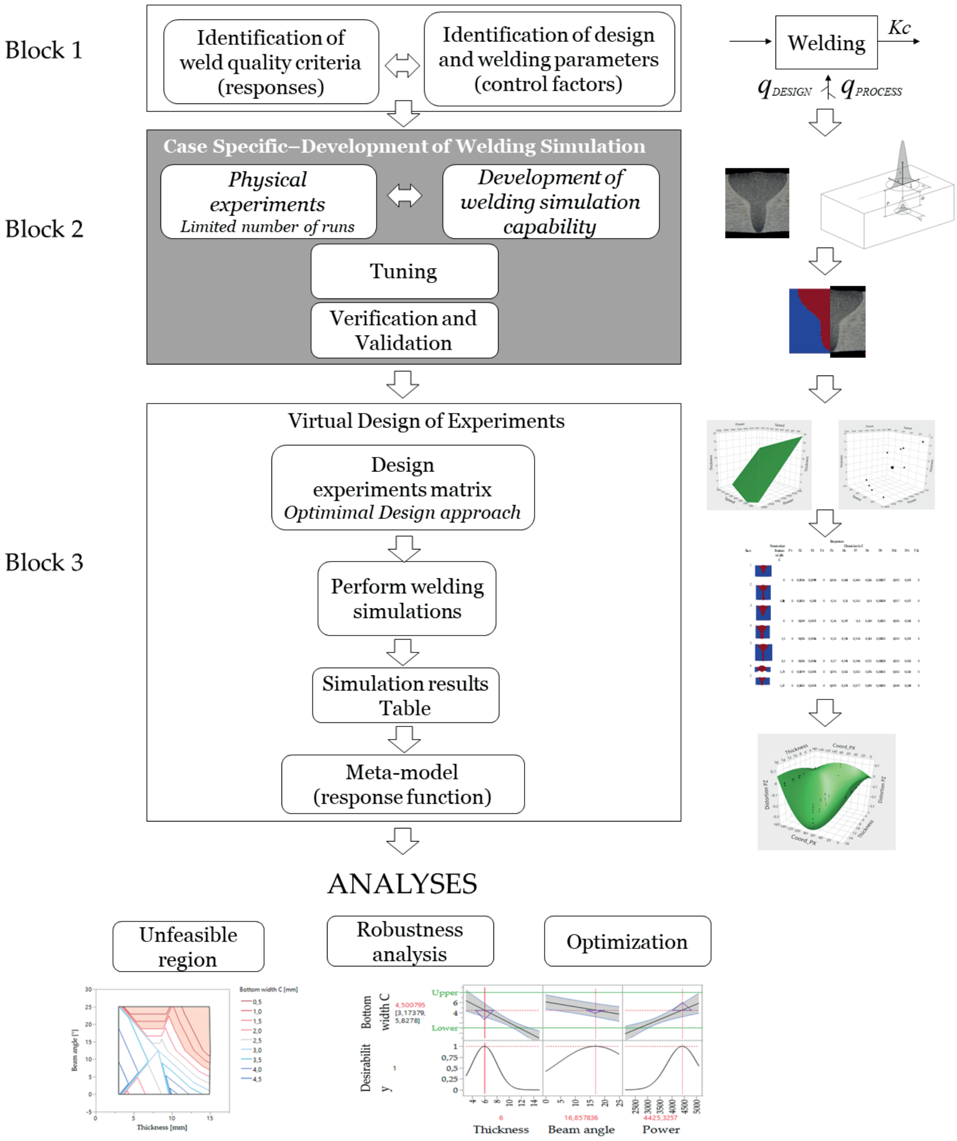

Figure 30 Virtual Design of Experiment method to build quantitative welding capability information

The metamodel allows the performance of three type of analyses:

1. The identification of unfeasible regions in the design-manufacturing space
2. The optimization of design and welding parameters
3. Robustness analysis

In addition, the metamodel built, representing the welding capability space, works as a predictor that can be employed to assess the producibility of future concepts.

In conclusion, applying this Virtual Design of Experiments method to obtain a metamodel brings a number of benefits. First, the use of DoE techniques allows exploring a large part of the design space, formed by selected design and welding parameters, requiring a minimal number of experiments. In particular, the use of Optimal Design as a DoE technique enables combinations of design and process parameters in the same experimental design. Second, welding simulation shortens the experimentation time, which opens up the possibility of performing a larger number of runs (simulation experiments) and combinations of factors compared to physical testing. In addition, welding simulation can provide a greater amount of detailed information concerning welding phenomena, such as the heat distribution and relationship to welding process parameters.

Therefore, by applying the proposed Virtual Design of Experiments method, additional welding capability information is gained at a lower cost. Gaining an early understanding of the welding process and its interaction with product design supports the decision-making during product design phases. With this method, quick analyses concerning welding producibility of a number of design variants can be performed during the early phases of multidisciplinary design of aerospace components.

4.2.8 (R8)—I.M.A.P. cycle- producibility control cycle

The results obtained until this point can be compiled into a producibility control cycle, which includes a number of activities. The producibility conceptual model (see Subsection 4.2.4) is the starting point with which to represent the fabrication process. In this model, it is possible to place the product key characteristics (KCs) that are being transformed operation by operation, as well as the contributors to variation of these KCs (the so-called producibility control factors, e.x q_{DESIGN}). The producibility conceptual model is a taxonomy that acts as an information framework for the following activities:

1) *Identify* what affects producibility
2) *Measure* what affects producibility
3) *Analyze* the effect of the interaction between factors that affect producibility
4) *Predict* producibility

These activities constitute the I.M.A.P. cycle and are outlined in Papers B, D and E.

Paper D presents a method based on the producibility model that prescribes how to identify KCs and design parameters (q_{DESIGN}) critical to those KCs. In addition, Paper D discusses ways in which to analyze the interaction between these producibility control factors combining qualitative and quantitative approaches (see 4.2.6). Paper E also builds upon the identification activity since welding process parameters ($q_{PROCESS}$) are also identified as producibility control factors. The measurement activity is discussed in Paper B. Paper B first presents a number of barriers to the measurement and inspection activities and then prescribes the producibility model as a core structure in order to identify *what*, *how*, *when* and *why* to measure.

In Paper E, the main contribution is to develop the analysis and prediction activities. The Virtual Design of Experiments method is proposed to obtain a metamodel with which to analyze and predict the effect of the interaction between design and welding process factors into weld quality (weld quality has been described by KCs in Subsection 4.2.7.).

The I.M.A.P. cycle has been implemented and tested in the global framework of the product development process. The objective has been to develop this producibility control cycle into a systematic framework for product development that enables producibility assessments for integrated products that are welded within a Multidisciplinary Design context.

To do so, two different industrial environments for multidisciplinary product development has been selected for implementation and validation: 1) Platform Design environment (Paper F) and 2) Multidisciplinary Design and Optimization (MDO) environment (Paper G).

4.2.9 (R9)—Producibility assessments in a Platform Design environment—Paper F

The first industrial product development environment within which to implement and validate the set of results in the form of a framework for producibility assessments is Platform Design. This study is the fruit of a cross-collaboration between the aerospace industry and a colleague research group at Chalmers which is investigating Platform Design. The research results are presented in Paper F.

Paper F presents an approach for generating a large number of product-manufacturing variants and simultaneously and systematically assessing their producibility by adopting Set-Based principles in the context of Platform Design (Figure 31).

To start with, an integrated platform is applied to model product and production variety, from which a number of product and manufacturing variants are generated. The variants are generated based on co-platforming and the reuse of intangible elements, i.e. the reuse of functions. Through function modeling, the product and manufacturing system together with manufacturing operations are co-modelled.

Thereafter, a two-stage producibility assessment approach based on two levels of screening is prescribed as a structured and systematic way in which to virtually assess and eliminate unfeasible variants and analyze further the remaining design variants generated by the integrated platform model.

The different variants are combinations of product design solutions, manufacturing design solutions and manufacturing operations. The producibility conceptual model presented in Paper C (see Figure 26) has been adopted to model manufacturing operations within an integrated platform (see also (Landahl et al., 2017)).

The producibility model is presented as a framework for identifying and connecting producibility control factors to the integrated platform. From the model, design parameters (q_{DESIGN}) are linked to welding producibility failures. These links are based on the WCAM guidelines presented in Paper D. What is new in this study is the categorization of the producibility failures and the resulting systematic analysis.

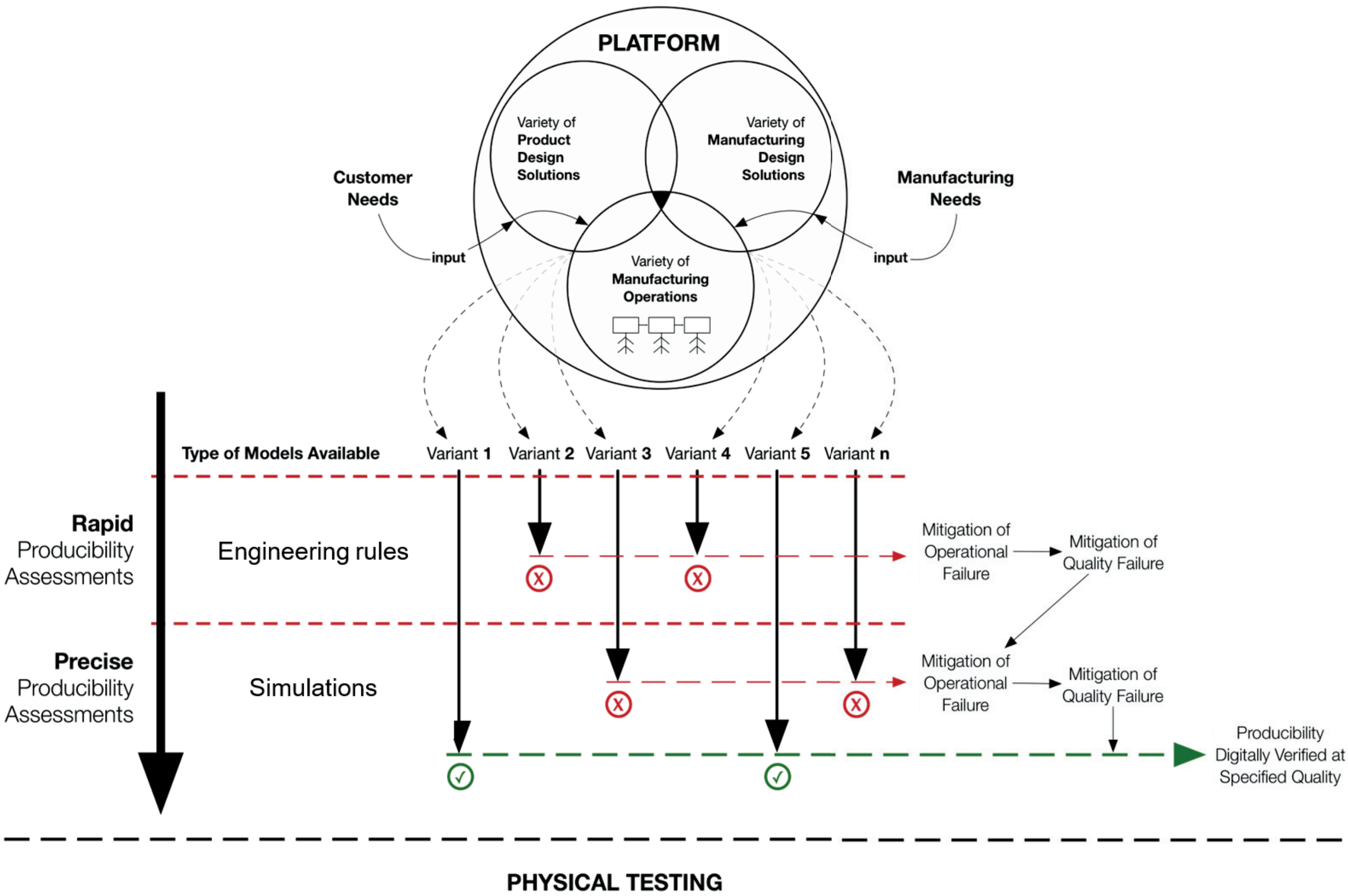

Figure 31 Two stage systematic producibility assessment in a Platform Design environment

First, Paper F provides a definition of producibility failures to meet the need of defining this concept within the field of Risk Assessment and Failure mode and Effect Analysis. "Producibility failures refer to failures that occur during the manufacturing process caused by the product design in combination with the selected manufacturing solution".

From this definition, two categories of producibility failures are proposed: Producibility Operational Failures and Producibility Quality Failures. The former ones inhibit the welding operation from being executed. The latter ones cause detriment in output weld quality.

This categorization allows screening of the product-manufacturing variants following a systematic order. First, Operational Failures are mitigated by eliminating the variants causing these failures. Thereafter, Quality Failures are mitigated.

In order to analyze the effect of the different product-manufacturing variants on the two types of producibility failures and proceed to elimination, two types of assessments are prescribed in this approach: Rapid Producibility Assessments and Precise Producibility Assessments. The difference between these two types of assessments lies in the level of detail in the product models and the type of input data available to perform the analyses. Rapid Assessments are conducted earlier when low fidelity models of the product-manufacturing design variants are available. Precise Assessments are conducted when more detailed information is gained by the models and simulation can be performed.

This approach is outlined in Paper F and validated in a case study. In the case study, a number of variants of aero-engine designs to be welded is generated from an integrated platform. These variants are systematically eliminated following the prescribed approach.

The two-stage producibility assessment and systematic elimination of variants based on Operational and Quality failures makes for this screening approach in communion with Set-Based Design principles.

4.2.10 (R10)—Producibility assessments in an automated Multidisciplinary Design and Optimization (MDO) Environment—Paper G

The second industrial product development context within which to implement and validate the set of results, in the form of a framework for producibility assessments, is an industrial automated Multidisciplinary Design and Optimization (MDO) environment. This study has been performed in collaboration with practitioners within the aerospace industry. The aim has been to develop and incorporate methods and tools to an industrial MDO environment in order to predict product quality after welding and control welding-manufacturing variation and defects. The research results are presented in Paper G.

Paper G proposes an approach with which to perform producibility analysis and trading-off these results with those from the analysis of remaining performance disciplines, such as Aerodynamics, Mechanical Engineering and Manufacturing Cost (see Figure 32).

The first step in the MDO producibility module involves constraining the formulation of the design space. First, a geometrical baseline model is analyzed with the use of the WCAM guidelines in order to identify design and related welding process parameters (q_{DESIGN} and $q_{PROCESS}$), which are connected to specific producibility failures. Thereafter, the design space can be constrained by employing existing producibility information and welding capability data (e.g. response surface based predictive models, rules, experimental data, graphs representing relationships between design and welding quality responses, etc.) stored in a CaPability DataBase (CPDB). This step is represented by a red arrow in Figure 32. In this way, unfeasible design variants, i.e. variants that will be unable to either be welded or achieve minimum levels of quality during welding, can be left out of the design space. The idea is to keep these guidelines alive by feeding it with new capability data and producibility control factors (q_S) identified each time there is a new product development process.

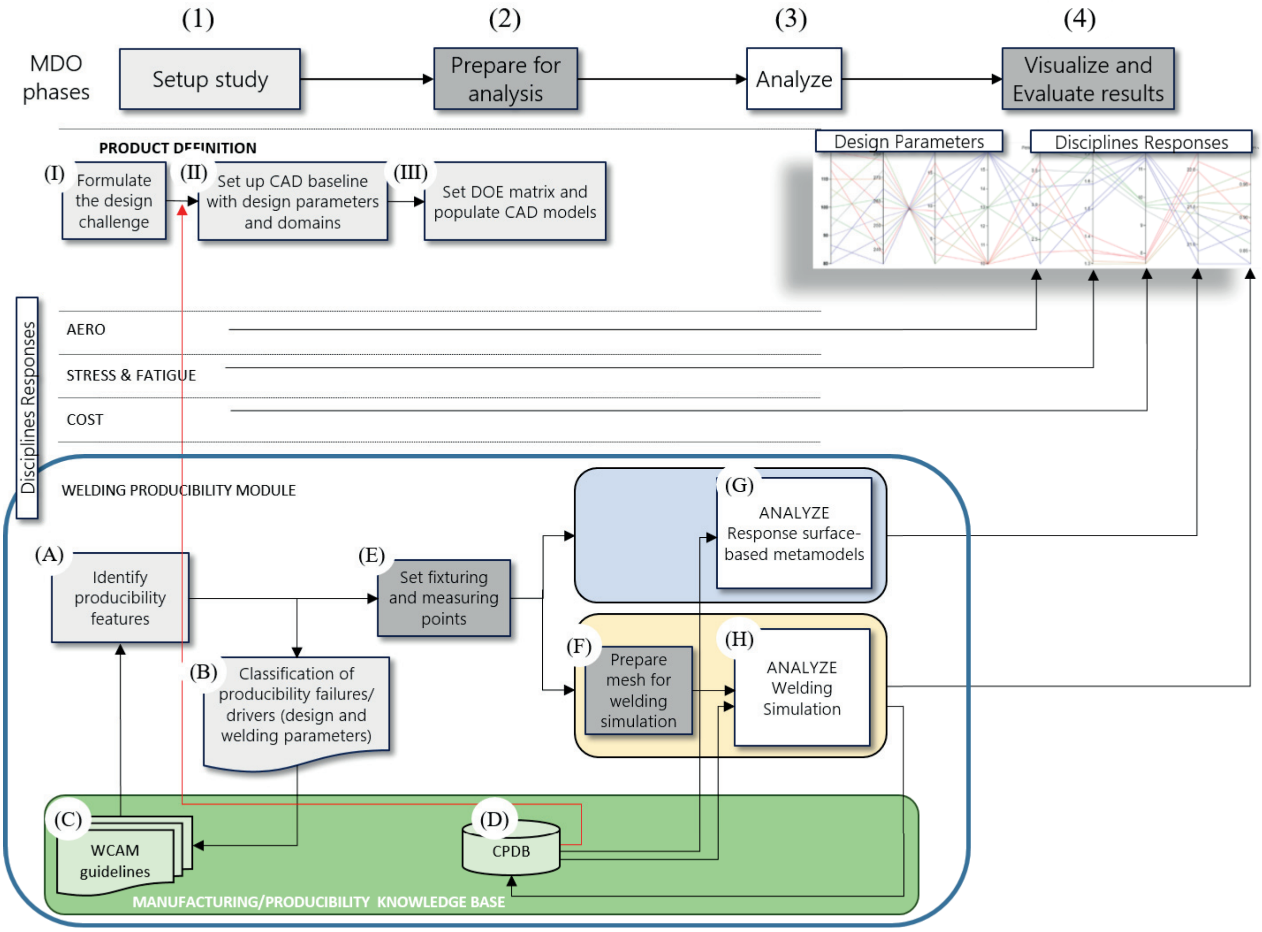

Figure 32 Producibility analysis module consisting of two analysis steps in a MDO enviroment

Having considered initial producibility constraints, the design space is populated adopting DoE techniques. In this case, the generation of variants is based on product geometry. There is a master CAD model (flexible or baseline CAD model), which is parameterized and from which design variants can be generated.

Once the design variants have been generated, depending on the type of producibility failure, two types of analysis can be conducted to systematically analyze the design variants within the producibility module. These analyses are based on: 1) Response Surface method and 2) Welding simulation.

Welding simulation is performed mainly to predict deformation, geometrical variation and residual stresses. The macroscopic deformation inflicted on a component due to fixturing and welding processes depends on the product geometry as a whole rather than on isolated design parameters. Therefore, for each new geometrical case and welding set up, new welding simulations need to be performed. However, there are cases in which either welding simulation cannot simulate and predict certain phenomena or it is too time consuming to conduct all simulation runs for each design variant. In these cases, there is a chance to employ response surface based predictive models.

The Response Surface method can generate predictive models based on either physical or simulation data (metamodels). The main idea behind Response Surface Methodology is to conduct a sequence of designed experiments (or computer experiments) in order to predict and evaluate the effects of multiple factors and their interactions into a response variable, as well as obtaining an optimum. These predictive models are built on studies different from the MDO study and can include the interaction of design and welding parameters. Thus, these models can provide detailed information about the behavior of the welding process. Response surface-based predictive models can be useful in those instances when the welding phenomenon and weld quality criterion that need to be predicted depend on isolated design parameters. For example, in Paper G, a response surface-based model built upon computer experiments (metamodel) has been employed to predict joint penetration since this response mainly depends on design parameter joint thickness and additional welding parameters.

The producibility constraints, derived from the CPDB to limit the design space generation, and the two step-analyses that can be performed in the producibility module constitute a systematic way for eliminating design variants that are non-producible and analyze the rest. Thus, this approach aligns with Set-Based Design principles.

In the final step of the MDO study (evaluation), graphs, such as parallel coordinates, are employed to visualize the results and evaluate the trade-offs between all disciplines, including producibility. These graphs help understating correlations, i.e. how the different values of design parameters constituting the design space interact and have an effect on the different discipline responses. Besides understanding interactions and effects, the information obtained can serve either to design a new and more detailed MDO study or to eliminate certain regions of the design space that become unfeasible or to rank the design variants. In a more detailed phase, multidisciplinary optimization can also be conducted by either weighting each response and optimizing it to an objective or by multi-objective optimization (Pareto optimization).

Furthermore, Paper G has also included manufacturing cost in the multidisciplinary evaluation. Thus, an holistic assessment of producibility, conceptualized into Quality and Cost, is completed.

The studies in Papers F and G bring the results from previous papers into the complete context of multidisciplinary design in product development. The steps with which to predict and control producibility and manufacturing variation have been adopted and implemented in two industrial product development environments (Platform Design and MDO) according to Set-Based principles.

The aim has been to equip the producibility stakeholder with the same tools and approaches that exist within the fields of Mechanical Engineering and Computational Fluid Dynamics in order to achieve similar levels of automated and virtual analysis during the multidisciplinary design process.

4.2.11 (R11)—Design for Producibility framework

The final research result, after the implementation of producibility assessments in two product development environments (Papers F and G), is the Design for Producibility framework.

The Design for Producibility framework provides a systematic approach to conducting producibility assessments of highly integrated performance welded products within a multidisciplinary design context. The core of this framework incorporates the activities within the I.M.A.P. producibility control cycle (*Identify*, *Measure*, *Analyze* and *Predict*) that contains an array of tools and methods (see Figure 33).

The studies in Papers F and G unfold *how* these activities, tools and methods are applied in a systematic way to a multidisciplinary design context coping with the principles of Set-Based Design. During Set-Based Design, a set of design variants is generated, analyzed and evaluated from different disciplines.

Figure 33 presents a summary of the activities, methods and tools contained in the framework and the systematization principles, which connect to Set-Based Design.

To start with, producibility failures and producibility control factors are identified and classified during the *Identify* activity.

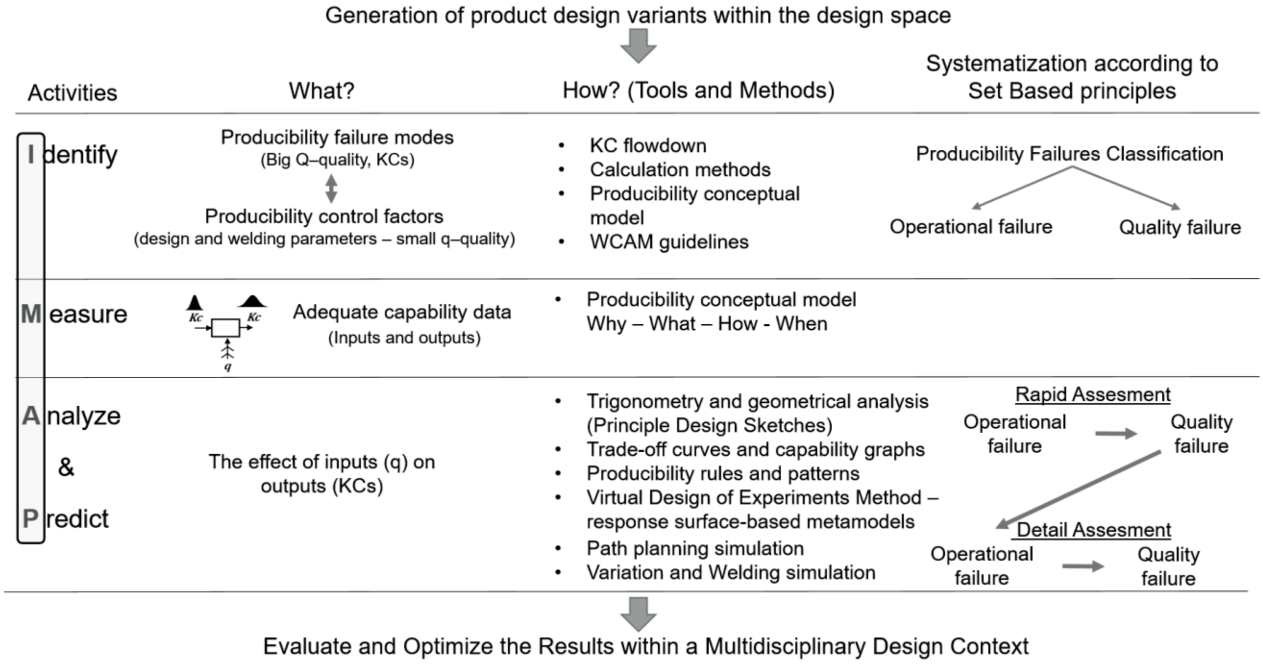

Figure 33 Design for Producibility framework-Producibility virtually verified

This identification serves first to influence the design space generation and, second, to prescribe the type of analysis that follows depending on the producibility failure categorization (Operational and Quality failures).

The *Measure* activity has the aim of collecting capability data (measure inputs and outputs). Thus, this activity is carried out for the cases in which data to perform the analyses for the set of design variants are missing, as shown in Paper E.

The systematization during the *Analysis* and *Predict* activities consists of two levels of screening (Operational and Quality failures) and two types of assessments (Rapid and Precise). In iterative loops of analysis, the design variants are analyzed, evaluated and eliminated (when applicable) to first mitigate producibility operational failures and thereafter producibility quality failures. The aim is to answer the question: *Can we produce this design and at what quality level?* Unfeasible variants are first eliminated and the quality output of remaining ones can be evaluated. The type of producibility assessments, Rapid and Precise, depends on the level of model information, input data available and complexity of methods. In addition, the methods for conducting analyses and predictions depend on the types of producibility failures and control factors.

For example, there are producibility failures for which patterns, capability graphs, engineering rules and response surface-based models available in a producibility knowledge data-base can be employed to analyze and predict such failures. In this thesis, two recurring examples of this type of producibility failure have been: 1) limited accessibility to weld and 2) joint penetration. The former has been categorized as an Operational Failure since it inhibits the welding operation from being executed, whereas the latter is a Quality Failure (for further explanation, please refer to Paper F).

In Paper F, a Rapid Assessment based on trigonometry and geometrical analyses has been conducted to first analyze geometrical combinations of different product geometries and welding gun positions (Principles sketches method in Paper F). The design variants that do not provide accessibility to weld (unfeasible variants) have been eliminated. Thereafter, trade-off curves connecting welding speed and joint thickness has been employed to analyze joint penetration quality for remaining variants.

In Paper G, a response surface-based metamodel has been employed to predict the effect of thickness, welding power, speed, and beam incident angle on joint penetration. In this case, the joint penetration analysis has also been preceded by a trigonometry and geometrical analysis to derive the values from the beam incident angle for the different combinations of product geometries and welding gun positions.

Therefore, in both Papers F and G, the Operational failure (limited accessibility to weld) has been first analyzed and thereafter the Quality failure (joint penetration), in this way providing a systematic order for screening the set of design variants.

However, there are other producibility failures for which more complex methods, such as simulations, need to be employed. These analyses represent the Detailed Assessments. In Paper F, a path planning simulation has been proposed to analyze the “limited robot rotation” Operational failure. Thereafter, a welding simulation has been employed to predict an “overlap in weld bead top side”, i.e. a weld bead geometry Quality failure (see also Paper D). In Paper G, a welding simulation has been employed to predict distortion, i.e. geometrical deformation, categorized as a Quality failure.

Furthermore, in each product development cycle, new prediction models can be built which can be stored in a database and reutilized for future projects.

In the final step of the Design for Producibility framework (see Figure33), the results of producibility analyses are evaluated and optimized together with the results of the other disciplines analyses.

5 Discussion

In this chapter, the research questions will be discussed and the quality of the results will be evaluated. The contribution this work makes to new knowledge is also considered.

The seven papers (Papers A-G) and eleven main research results (R1-11) presented in this thesis contribute to answering the four research questions (RQs) posed in the Introduction, as indicated in Table 7. The answer to each RQ is presented in the coming section.

Table 7 Connections between results, papers, study areas, DRM phases and research questions

Results		Study Area		Descriptive Study I		Prescriptive Study			Descriptive Study II
Main	Paper	Design	Manufacturing	RQ1	RQ2	RQ3	RQ4.1	RQ4.2	Validation
R1 (4.2.1)	A	√			✈				
R2 (4..2.2)	A	√		**✈**					
R3 (4.2.3)	B	√	√	**✈**		✈			
R4 (4.2.4)	C		√		**✈**				
R5 (4.2.5)	C & D		√		**✈**				
Lit. Rev.	D	√		✈					
R6 (4.2.6)	D	√	√			**✈**			
R7 (4.2.7)	E	√	√	✈		**✈**			
R8 (4.2.8)	Thesis						**✈**		
R9 (4.2.9)	F	√		✈				**✈**	✈
R10 (4.2.10)	G	√		✈				**✈**	✈
R11 (4.2.11)	Thesis							**✈**	

✈ strong contribution; ✈ low contribution Lit. Rev.=Literature Review

5.1 ANSWERING RESEARCH QUESTIONS

RQ1: What are the barriers encountered when making producibility assessments during the design process of fabricated aerospace components?

The answer to this question is provided by the two main research results R2 and R3. These results have been compiled to a great extend from Papers A and B. Nevertheless, additional insights gained in the studies performed in Papers D, E, F and G have also contributed to these two main results, thus, to answer RQ1 (see Table 7).

In summary, the barriers that might hinder the implementation of some reviewed methodologies and tools for making producibility assessments of highly integrated fabricated structures during the multidisciplinary design process include:

1. The lack of producibility criteria related to product quality.
2. The subjective nature of existing information about producibility based on expert opinions.
3. The lack of guidelines including know-how and structured expert knowledge for new and advanced materials and welding technologies.
4. The lack of welding capability knowledge and quantitative data with which to perform optimization and evaluate trade-off alternatives between producibility and other disciplines during multidisciplinary design analysis.
5. The lack of quantitative methods with which to evaluate producibility.
6. The lack of virtual tools (lack of predictive models and incomplete simulations).

In theory, the use of methodologies, such as Systems Engineering and Set-Based Concurrent Engineering, is practical to set up and verify requirements. Set-Based Concurrent Engineering is a convenient approach with which to analyze the design space in a systematic way, as well as building knowledge and facts about the different product concepts (design variants) during multidisciplinary design.

However, producibility as a criterion and manufacturing as a stakeholder are still not fully considered in these methodologies. The assessment of producibility and manufacturing capability based on CAD geometry is, if possible, mostly limited to interactive and manual analysis of a single design.

The DFM and DFA methods can to some extent be useful. However, for the case of welded aerospace structures, these methods present some barriers and limitations connected to the type of product and process application, and optimization focus. DFA and DFM focus on optimizing time and cost, rather than quality, in forming and assembly processes such as screwing, riveting etc. Instead, the joining process of welding is vaguely treated in traditional DFA examples. Furthermore, common products applications of traditional DFM and DFA methods are complex products in the number of parts for which geometrical and structural modifications do not substantially affect product performance and functionality. Consequently, DFA and DFM recommendations on geometrical and structure simplifications can be conducted to reduce manufacture and assembly complexity and thus production time without compromising product functionality.

However, the products and applications that build the context of this thesis, welded aerospace components, are highly integrated solutions, in which geometry is strongly linked to performance (*geometry influences function*). At the same time, the manufacturing solution influences geometry and geometry in turn influences the producibility of the manufacturing solution (*geometry influences producibility*). This means that either a geometrical or a structural modification of these products will have an impact on product performance and quality outcome of the manufacturing process. It is because of this coupling between design and manufacturing that manufacturing variation of key product characteristics and thus the quality built into the product during its fabrication becomes the critical issue in welded aerospace products.

Therefore, producibility criteria and assessments cannot solely rely on optimizing time and cost spent on manufacture and assembly but rather on the quality built into the product.

The same underlying problem regarding product and process application occurs in Product Risk Assessment methods, such as Failure Mode and Effect Analysis (FMEA), as studied in Paper F. Design-FMEA methods focus on design failures during product use. Instead, process-FMEA methods focus on failures of the manufacturing system. However, there is no FMEA method that considers potential producibility failures caused by product design. The lack of consideration of producibility failures in FMEA methods can be related to the decoupling between design and manufacturing, which can be included when dealing with modular products and those whose geometry is not highly linked to manufacturing quality.

Besides the lack of detailed criteria with which to measure and evaluate producibility, one of the main barriers to perform producibility assessments is the lack of corresponding quantitative data. In addition, there are less automation and simulation capabilities to predict and mitigate producibility problems in comparison to other disciplines, such as aerodynamics and mechanical engineering.

The complexity of the welding process and the barriers to evaluate welding quality virtually makes the understanding of causes and effects during the early phases of the multidisciplinary design process of aerospace components (design space exploration and analysis) still rely to an extent on expert judgements.

However, one may wonder why current manufacturing and inspection data are not being utilized to perform producibility evaluations. In the aerospace industry, a 100% inspection is the norm due to safety reasons. In the digital age, where Industry 4.0 has emerged, there is a major potential to monitor, record and produce data about everything that concerns production systems. From Big Data, manufacturing data can be smartly re-utilized during coming design activities. These data could be utilized to perform simulations and build statistical models to virtually ensure product quality and to make products more robust against manufacturing variation. However, the current industrial situation shows that manufacturing data are employed mainly to monitor and control production, as well as for process optimization and rework practices. But, why are manufacturing/inspection and process capability data not reused in design activities today? Paper B gives an answer by identifying and classifying specific barriers to the reuse of manufacturing and inspection data during robust design activities. These barriers are classified into information, technical and organizational barriers.

This thesis and Paper B in particular focus on analyzing information barriers. Information barriers relate to the quality of data content. The information aggregated from measured data is not suitable for analysis in probabilistic-based design activities. This problem can be broken down into four sub-questions, *why*, *what*, *how* and *when to measure*. If these items mentioned are not defined in a structured way, suitable process capability data will not be obtained.

Therefore, to produce pertinent and adequate manufacturing data to be reused in future design activities, it is imperative to identify the elements within the manufacturing process that define and affect producibility, leading us to the next research question.

RQ2: What affects and defines the producibility of a fabricated aerospace component during its manufacturing process?

This question is first addressed by the producibility term analysis, definition and metrics presented in Paper A (see also the corresponding main research result R1). Thereafter, the main research results from Paper C and D, R4 and R5, complete the answer to this question by presenting a producibility conceptual model and an example of a generic application for welded aerospace components (see Table 7).

Producibility is the preferred term over manufacturability for the case of welded aerospace applications. This argumentation can be found in Paper A. With manufacturability and traditional DFM, the goal has been to modify product structure and product form for the purpose of optimizing production time and cost. Major consideration is given to process and less to product function and product characteristics. However, in integrated aerospace components that are welded, there is a strong coupling between product geometry and functionality and between product geometry and welding producibility (understood as geometrical and weld quality). Thus, manufacturing variation in key product characteristics becomes a critical issue. This is the reason why in aerospace applications, the producibility term embraces something else, allowing the shift from process orientation towards product orientation. The product quality, thus product form and structure, become the main focus. Ensuring product quality during manufacturing becomes more important than the optimization of production time.

Based on this argumentation, Paper A gives a definition of producibility: "*Producibility is the capability to produce the product in a robust and efficient way to meet the design specifications for functions and reliability of the product"*.

However, this definition is not sufficient to measure producibility. If the ultimate purpose is to evaluate and predict producibility, this concept first needs to be conceptualized, operationalized and thus defined.

Producibility is an emerging property from the interaction of two technical systems, the product/design and the manufacturing system. Producibility already emerges from the early phases in the design process where design structure and product characteristics are being specified and production solutions are being considered. However, producibility only gets tangible during the manufacturing process when product/design and manufacturing systems meet physically for the first time. Quality and cost are consequences of producibility and metrics that can be used for its conceptualization and definition as argued in Paper A. The quality concept is taken from Quality Engineering Theory. Thus, quality is achieved if the output variation of the manufacturing operation is within tolerance limits. Thus, a quality failure occurs when output variation is outside tolerance limits.

The cost concept does not only cover material and production cost. It also covers the cost of quality failure. In aerospace applications, scrap rates are extremely low. Thus, quality failures during production are fixed through rework or sometimes even through redesign loops.

Consequently, in aerospace applications, the focus is shifted towards quality and how quality is being built into the product during its manufacture (see Figure 34).

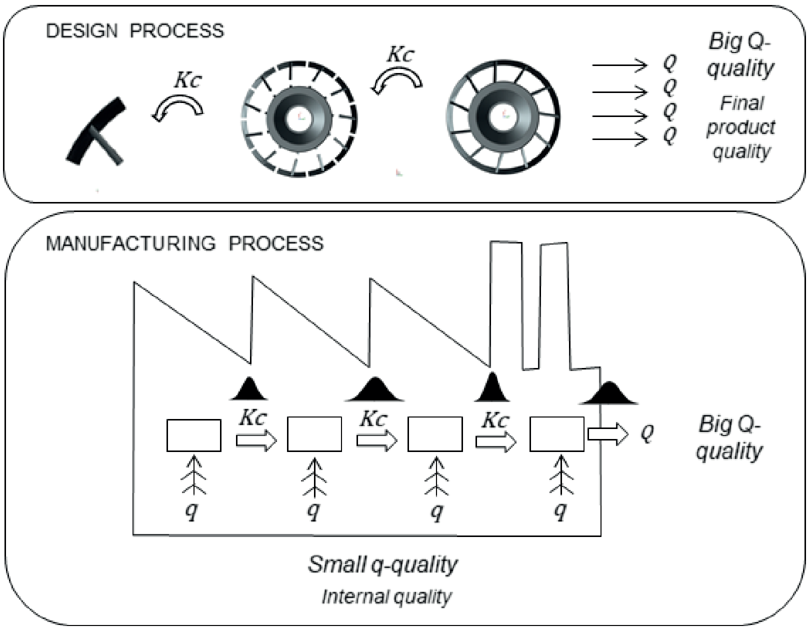

Figure 34 Phenomenon representation: Product quality creation

Therefore, in order to operationalize producibility and be able to measure and then evaluate it, there is a need to model the quality creation during the manufacturing process to show how variation is created and propagated operation by operation (see Figure 34). In Paper C, the producibility conceptual model is proposed to describe product quality creation during a fabrication process. See Figure 26 in the Chapter 4.

The producibility conceptual model represents the key product characteristics (KCs) created and transformed operation by operation, which carry product quality (Q). In addition, the model represents the producibility control factors (q) that affect that transformation contributing to variation on these KCs, thus impairing product quality.

In the producibility conceptual model, the manufacturing operation is modeled as a transformation system consistent with the Theory of Technical Systems (TTS). However, unlike what TTS states, in this transformation, the manufacturing equipment is not the only Technical System (TS) affecting the transformation. Instead, there are two technical systems (product and manufacturing) and the interaction between both which contribute to the transformation process (TrfP), as shown in Figure 35.

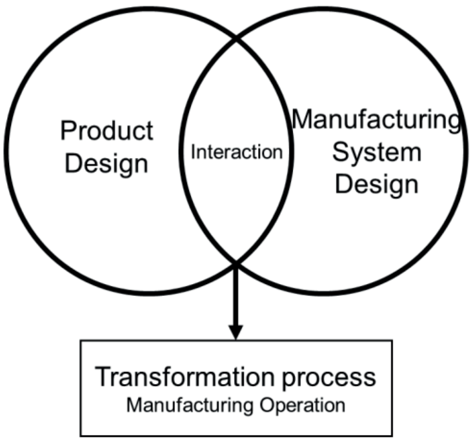

Figure 35 The interaction of two systems (Product and Manufacturing) affects the transformation process that occurs during a manufacturing operation

This means that what affects producibility stem from elements of these two systems in interaction, emphasizing that not only the choice of equipment and process parameters ($q_{EQUIPMENT}$, $q_{PROCESS}$ and q_{METHOD}) but also the design of the product, i.e. which design parameters and material are chosen (q_{DESIGN}, $q_{MATERIAL}$), will have an effect on producibility.

To understand what affects and defines producibility, producibility has been conceptualized as quality. At the same time, quality has been operazionalized by defining the KCs and producibility control factors (q_{DESIGN}, $q_{MATERIAL}$, $q_{EQUIPMENT}$, $q_{PROCESS}$ and q_{METHOD}) in the producibility model.

The fact that design parameters (represented in the category q_{DESIGN}) are acting as producibility control factors in the manufacturing operation is a sign of the existing coupling and interaction between design and manufacturing in these types of applications. It is important to identify the design parameters falling under this category due to the fact that Design for Manufacturing and Assembly (DFMA) actions will have to be taken based on them.

The proposed producibility model works as a taxonomy, i.e. as an information framework, with which to support identification and classification of product characteristics carriers of quality (KCs) and producibility control factors (q_S) that define and affect producibility.
Additionally, Papers C and D (see also result item 4.2.5) present an exhaustive breakdown and identification of all key product characteristics (KCs) and producibility control factors (q_S) in the case of welded aerospace components.

RQ3: How can producibility information and data be generated to support integrated development during multidisciplinary design of fabricated aerospace components?

There is a lack of manufacturing capability data and quantitative data with which to perform optimization and evaluate trade-off alternatives between producibility and other disciplines during design space exploration and analysis in multidisciplinary design, as discussed in the answer to RQ1.

This deficiency indicates first a need to structure and automatize expert knowledge and second, a need for virtual assessment methods and for planning systematic experimentation to obtain sensitivity coefficients within the welding system and produce adequate process capability data that can be used in design stages. The third research question aims at solving this barrier.

The answer to the RQ3 is first introduced in Paper B and the main research result R3. However, the core answer to this question comes from the methods and tools presented in the main research results R4, R6 and R7, from Papers D and E (see Table 7).

Paper B argues that a structured approach to clarifying *why*, *what*, *when* and *how* to measure would enable the creation of adequate manufacturing process capability data and producibility information to be utilized during the design process.

The first step to generate such data is to answer to the question *Why to measure* by implementing a Quality Assurance cycle to identify users of process capability data. Thereafter, the producibility model proposed in Paper C (Figure 26) would connect user needs to measuring data in order to pull the required producibility information by answering to the question *What and When to measure in the fabrication process*.

The producibility model is the starting point for supporting systematization on how to identify all key product characteristics (KCs) and producibility control factors (q_S). However, the model by itself does not prescribe *How* to identify and analyze either the relationship between these variables or sensitivity coefficients, which would help to generating pertinent producibility information and process capability data. To solve this problem, Papers D and E go a step further.

Paper D uses the producibility model presented in Paper C as a basis for building the Welding Capability Assessment Method (WCAM). The WCAM method consists of a number of steps and tools with which to identify and analyze KCs and producibility control factors connected to design parameters (q_{DESIGN}) (see Figure 28 in Chapter 4).

In the first step of the WCAM method, a KC flowdown is applied and aligned to the assembly process to break down product technical requirements into KCs at each product subsystem level. The KC flowdown enables the identification of which input and output KCs need to be measured at each operation. Defining requirements and tolerance limits at each operation by pulling information from the final customer allows building product quality and value proactively.

In the second step of the WCAM method presented in Paper D, the so-called WCAM-guidelines are presented as a mean of first, identifying potential producibility failure modes within the welding system and, second, connecting them to design parameters (q_{DESIGN}) that act as causes. Each welding producibility failure mode is connected to specific output KCs.

Once control design parameters (q_{DESIGN}) acting as independent variables (X) and output KCs acting as dependent variables (Y) have been identified, the objective is to analyze relationships between both variables and evaluate sensitivity coefficients. The aims is to build models, patterns and engineering "DFM" rules in order to generate adequate producibility information and process capability data.

Since expert knowledge still plays an important role when evaluating welding producibility, Paper D demonstrates the strength of combining qualitative and quantitative analyses to generate adequate producibility information and process capability data.

The WCAM-guidelines are a first attempt of structuring expert knowledge. In the guidelines, a positive or negative relationship between welding producibility failure modes and design parameters is indicated. For example, increasing joint thickness will enhance the risk of incomplete joint penetration (the material does not fuse throughout the weld depth). However, this qualitative information needs to be completed with information of quantitative nature. For example, how thick can a joint be to still achieve complete penetration?

Paper D employs welding simulation to analyze the effect of two design parameters (radius and joint thickness) on weld bead geometry (joint penetration). However, in this study only main interactions have been covered.

Paper E further addresses this need for quantitative producibility data. Paper E presents a Virtual Design of Experiment method to model the effect of design and welding parameters (q_{DESIGN} and $q_{PROCESS}$) on weld quality (more specifically KC: weld bead geometry and KC: geometrical distortion).

One of the core contributions of this method is to combine DoE techniques with welding simulation, which prescribes a systematic plan with virtual experiments to generate pertinent producibility information and be able to evaluate interactive-coupling effects between parameters.

The result is the creation of a response surface-based metamodel that contains quantitative information about the effects and sensitivity coefficients between producibility control factors (q_S) and KCs. With the metamodel, producibility responses of parametric combinations within the design space that have not been simulated can be estimated.

Besides the benefits of shortening experimentation time, welding simulation also provides extended and detailed information about welding phenomena, including the thermal field. Therefore, by applying the proposed Virtual Design of Experiments method, welding capability information is generated at a low cost.

Welding simulation is a source of producibility data and information. Nevertheless, simulating welding is not an easy task due to the complex multi-physical phenomena occurring during the welding process, in addition to the many process outputs. Furthermore, every new application (i.e., new materials, welding technology, welding set-up and product geometry) can entail new challenges to welding simulation due to the strong coupling that exists between product geometry, set-up and welding quality outcome. In many cases, welding simulations may need to be developed to predict weld quality outcomes and provide information about the welding process. For example, as a part of the research work presented in this thesis, a new heat source model was developed to model the effects of part thickness, welding beam angle parameter, welding power and speed on the weld bead geometry and geometrical deformation (distortion), (see Paper E).

In summary, the compilation of results presented in Papers B, D and E (the producibility model, the WCAM guidelines and methods, and the Virtual Design of Experiments method) forms collectively an array of tools with which to generate producibility information and process capability data that allow searching for design solutions at acceptable welding capability levels within the design space. This array of tools enables the combination of simulation and manufacturing data together with patterns and engineering rules extracted from specialized information about welding problems and know-how. This combination provides an holistic and complete information to perform welding producibility assessments during the multidisciplinary design process of fabricated aerospace components.

RQ4: How can producibility assessments be conducted and implemented during the multidisciplinary design process of fabricated aerospace components?

RQ4 contains two parts. One part relates to how producibility assessments can be conducted. The answer to this first part is provided by the main research result R8 (developed in Papers A to E). The second part relates to the implementation of these producibility assessments in the bigger context of multidisciplinary product development. The answer to the second part of RQ4 is provided by the main research results R9, R10 and R11, which have been developed from the studies performed in Papers F and G (see Table 7).

RQ4.1) How can producibility assessments be ***conducted*** *during the multidisciplinary design process of fabricated aerospace components?*

In order to conduct producibility assessments during the multidisciplinary design process of fabricated aerospace components, there is a need to provide equivalent virtual tools and methods as those employed during the analysis of the other performance disciplines.

The compilation of results from Papers A to E constitutes a producibility control cycle (I.M.A.P. cycle, see main research results (R8) in Subsection 4.2.8 within Chapter 4). This cycle prescribes in a structured way a number of phases and activities within which virtual methods and tools are proposed to conduct producibility assessments in the case of welded high performance components.

The producibility model (R4&5), WCAM guidelines and methods (R6) and Virtual Design of Experiment method (R7) prescribe ways to:

1) ***I****dentify* what affects producibility
2) ***M****easure* what affects producibility to generate pertinent process capability data
3) ***A****nalyze* the effect of interaction between factors that affect producibility, thus drawing the manufacturing capability space
4) ***P****redict* producibility

The methods and tools within the I.M.A.P. cycle combine specialized knowledge and experimentation with simulation capabilities to quickly explore the design space by analyzing a large amount of design variants.

When analyzing the design space, expert knowledge can serve to identify potential producibility problems and argue for causality once quantitative methods have proven correlations between design parameters and welding quality outcomes. The WCAM guidelines employ expert knowledge and theory with which to establish relationships between design parameters and welding producibility failure modes. The guidelines also provide an indication as to whether this “correlation” is positive or negative.

To statistically quantify correlations and interactions, the Virtual Design of Experiments method employs DoE techniques to generate response surface-based metamodels with the use of simulation which allows the concurrent evaluation of the design space in terms of producibility along with the other disciplines (e.g. aerodynamics). Besides prediction, activities that can also be performed from the metamodel include finding unfeasible regions in the design space, robustness analysis and optimization. These predictive models allow the analysis of a large number of geometrical design variants without the need for conducting additional virtual or physical experiments.

Welding simulation is important when there is a need to predict geometrical distortion (i.e. macro-deformations) for a large number of geometrical product variants. Metamodels can be unfeasible for the evaluation of these types of producibility failures. The reason is that building rules and metamodels becomes difficult in the case of highly integrated geometrical welded components because distortion and geometrical deformation are so dependent on product geometry, i.e. many design parameters have an effect on geometrical deformation.

Nevertheless, there are producibility failures, such as those related to weld bead geometrical quality (e.g., joint penetration) for which isolated design parameters can have an effect on the producibility response. In these cases, response surface-based predictive models and metamodels can be created by including just a few design parameters as input factors, as demonstrated in Paper E.

Gaining early understanding of the welding process and its interaction with product design supports decision-making during product design. Given the methods and tools proposed, quick analyses concerning welding producibility of a number of design variants can be performed thereby supporting a complete integrated development during the multidisciplinary design of aerospace components.

The ***I.M.A.P.*** *cycle* constitutes the core of the Design for Producibility framework proposed in this thesis. The author´s intention is not to replace current frameworks, methodologies and cycles that can be found in literature, such as D.M.A.I.C. (from Six Sigma) or I.A.M. (from Variation Risk Management); see Chapter 2. The I.M.A.P. cycle shares similar phases and purpose. However, one of the main contributions of this thesis to academia and industry is the model and methods presented in I.M.A.P., which are specially tailored to conduct producibility assessments during the design process of welded highly integrated performance components.

*RQ4.2) How can producibility assessments be **implemented** during the multidisciplinary design process of fabricated aerospace components?*

In order to manage producibility and assure manufacturing quality during design stages it is important to combine:

- Automated and structured welding expert knowledge and know-how
- Capability data that contain information about the impact of design on the welding process
- Welding simulation results
- Predictive models, such as response surface-based models and metamodels

The I.M.A.P cycle prescribes ways to generate and analyze these data in order to perform producibility assessments.

Nevertheless, the activities and methods within the I.M.A.P. cycle need to be conducted in a systematic way and implemented within the context of multidisciplinary integrated product development.

As first explained in Chapter 1 and throughout the thesis, for integrated products of high performance, the preferred way of working during design phases is applying Set-Based Design principles. In order to obey Set-Based principles, there is a need for systematic analysis, building knowledge and subsequent screening of design variants.

Therefore, the I.M.A.P. cycle has been incorporated into a Design for Producibility framework (R11) in order to systematize producibility assessments according to Set-Based principles in the overall context of integrated product development and Multidisciplinary Design. A summary of the framework containing a scheme of systematization has been presented in Figure 33 (see also R11, in Subsection 4.2.11).

This Design for Producibility framework has been developed and validated throughout Papers F and G, in which the activities and methods within the I.M.A.P. cycle were implemented and tested it into two realistic integrated product development environments.

Paper F studied how to conduct and implement producibility assessments in a (1) Platform Based Design environment, whereas Paper G focused on (2) an automated Multidisciplinary Design and Optimization (MDO) industrial environment. Both environments, (1) and (2), are ruled by Set-Based Concurrent Engineering (SBCE) principles. The main difference between them is the way in which design variants are generated. In the study of Platform Based Design presented in Paper F, variants are generated based on the reuse of functions (intangible elements), whereas in the automated MDO environment tested in Paper G, the generation of variants is founded on product geometry.

Systematization can be performed based on different analyzes-assessments stages and levels of screening depending on the nature of producibility problems and the design and process parameters involved (see the scheme for systematization within the Design for Producibility methodology in Figure 33).

The first stept, after design variants have been generated, is to evaluate the design and identify potential producibility failures connected to specific design parameters (q_{DESIGN}) with the help of the WCAM guidelines. To systematize the identification and analysis activities, producibility failures can be classified into operational and quality failures. This categorization allows for analyses and screening of the product-manufacturing variants following a systematic order.

First, operational failures are mitigated. The design variants that provide a negative answer to the question, – can we produce "this design"? , i.e. unfeasible design variants, can be eliminated.

Thereafter, the remaining design variants are assessed to mitigate quality failures. In this case, the underlying question is – at what quality level can we produce "this design"?. At this screening level, the expected product quality after welding of the design variants is evaluated. The design variants that prove to cause inferior quality levels during production can be eliminated. The remaining design variants can be optimized according to quality criteria.

At the same time, to conduct this screening approach, analyses of product-manufacturing variants are performed in two stages (see Figure 33). During conceptual phases of product development when low fidelity models are available, Rapid Producibility Assessments can be performed, within which analyses are conducted employing DFM engineering rules, patterns, capability data and predictive models. In latter stages, Precise Producibility Assessments are conducted when more detailed information is gained about the design models, and simulation can be performed. Furthermore, the type of assessment can be determined depending on the type of producibility failure to assess and input data-information available at each stage.

Once the producibility of the design variants have been assessed and welding quality levels predicted, the results can be traded off against the results from the other disciplines to ensure an integrated multidisciplinary design process. The objectives can be to understand correlations between the design and the different discipline responses, as well as performing robustness analyses and optimizing the design.

The result from both studies (Papers F and G) is a structured and systematic way to virtually analyze and eliminate the unfeasible design variants from a producibility perspective at the same time as knowledge is built and remaining variants are further evaluated and optimized.

The final result is a product for which producibility has been virtually verified. Thereafter, planning for physical experimentation to verify results will be necessary until enough maturity has been acquired in simulation models. However, the objective is to reduce the physical testing phase as much as possible.

The systematization of the I.M.A.P. cycle within multidisciplinary product development environments according to Set-Based principles completes the Design for Producibility framework.

5.2 PLATFORM-BASED DESIGN vs AUTOMATED MDO

This section discusses the differences between the two product development environments selected to implement the activities and methods proposed in this thesis with which to perform producibility assessments.

In Paper F, producibility assessments are conducted and implemented in an industrial Platform Based Design environment. In this product development environment, design variants are generated based on co-platforming of product and production solutions. In the study, co-platforming has been enabled by employing a functional modeling technique (Function–Means

F–M modeling), which allows the reuse of intangible elements, i.e. the reuse of functions. Applying co-platforming using F–M modeling has brought the advantage of an integrated development between product and manufacturing. With this approach, the generation and evaluation of product-production solutions can be started already during conceptual phases when detailed geometry data are not available and only abstract data can be considered. In addition, with the application of the first axiom of Axiomatic Design (see (Suh, 1990)) to the F-M modeling technique, product functions can be decoupled, which enables modularization at a functional level (Söderberg and Johannesson, 1999, Johannesson and Söderberg, 2000).

However, the problem arises when solving requirement conflicts at a geometrical level in the case of highly integrated designs, as the ones described in this thesis. At the functional level, functions can still be decoupled, but at a geometrical level, everything is integrated. In a geometrically integrated design, requirements cannot be solved one-by-one, independently. Thus, a solution designers can adopt is to apply multidisciplinary design optimization (MDO), the reason why MDO is a common product development environment in the aerospace industry.

In the automated MDO industrial product development environment tested in Paper G, the generation of variants is founded on product geometry. Generating variants from a geometrically based point is a common approach in the development of aerospace components, in which designs have not been subjected to drastic changes. However, considering baseline geometries can limit design space generation as discussed by Müller (2018) and Borgue et al. (2018). An additional disadvantage is that there is not an explicit co-modeling of product and manufacturing solutions, when compared to co-platforming. However, constraints from producibility, as from other disciplines, can be considered when populating the design space in an MDO environment, as shown in Paper G.

The two environments, (1) Platform Based Design and (2) Automated MDO, selected to test the Design for Producibility support proposed in this thesis are not exclusive environments. The design exploration process of highly integrated products can start with co-platforming. This approach can be applied to elicit novel solutions in early conceptual stages of the design process. During these stages, the support proposed in this thesis can be employed to evaluate the producibility of the conceptual variants based on abstract data, as shown in Paper F.

Thereafter, MDO can be applied to solve the integrated design in later design stages when more detailed data and information have been gained about the geometrical models. The framework, methods and tools proposed in this thesis ensure that producibility is evaluated and optimized during the application of MDO, as shown in Paper G.

5.3 THESIS RESULTS IMPACT

5.3.1 Scientific contribution

The academic contribution is a dual contribution. The first main contribution is understanding and generating knowledge about two phenomena: 1) how designers make producibility assessments in multidisciplinary design and the barriers within Engineering Design methods and tools. 2) how producibility is created during the fabrication process and the sources of variation in welded products. The results are a classification of barriers to perform producibility analysis during design processes and a producibility model to represent the product quality creation during the manufacturing process.

The second main contribution is providing a framework with a roadmap of activities containing a conceptual model (producibility model) and an array of tools and methods (the WCAM guidelines and methods, and the Virtual Design of Experiments method) for Variation Management and Quality Assurance tailored to high performance welded products.

With this support, the author intends to make a contribution to the field of Quality Engineering and, more particularly, to Geometry Assurance by expanding the support to the particular case of welding quality.

5.3.2 Industrial contribution and support evaluation in the context of DRM

One of the challenges of Applied Research and Design Research in particular is to deliver results that are relevant and applicable to industrial needs. Methods and tools for practitioners are common research results, from which usefulness and applicability to industry must be guaranteed to avoid ending up in a "valley-of-death" situation between academia and industry, as described by Flyvbjerg (2006).

The industrial contribution of this thesis involves the creation of a framework to produce capability data and producibility information, as well as performing producibility assessments during design space exploration and analysis of fabricated aerospace components according to Set-Based principles. The framework, methods and tools proposed support designers to predict virtually and rapidly the manufacturing quality of a large number of product design variants during the multidisciplinary design process of fabricated aerospace components.

This thesis has been conducted within the framework of Design Research Methodology (DRM). The Descriptive Study II within this framework has the aim of evaluating the applicability and usefulness of the support generated during the Prescriptive Study. The applicability and usefulness of the support proposed in this thesis can be evaluated with the help of Success and Measurable Criteria.

The Success Criteria in this thesis have been defined as: *increase final product quality (after the fabrication process) and decrease number of rework, i.e. quality failure cost*. This selection is based on the producibility dimensions quality and cost, as defined in the thesis.

These Success criteria can be explained as: the thesis support will be useful, once production has started, if the products manufactured acquire a higher final quality and quality failures have decreased, thus reducing rework and ultimately production cost.

However, a Measurable Success Criteria have been selected due to the impossibility of evaluating the Success Criteria within the research project time frame.

During the Descriptive Study of this thesis, the initial industrial situation revealed that producibility evaluations in early phases relied mostly on expert judgements and physical testing. Producibility assessments were performed based on rules of thumb extracted from previous experiences. Still, a few producibility evaluations were conducted virtually with the use of welding simulations. However, the simulation was mainly directed at evaluating distortion (geometrical deformation). In addition, welding simulations were conducted on a single detailed design, which was already optimized in terms of performance, such as product life, aerodynamics, weight, etc. This situation led to producibility problems during production, impacting negatively on total quality and cost. The reader can also refer to the final part of the main research result (R2), presented in Subsection 4.2.2., in which a list of requirements for the support developed in this thesis was established after research gaps has been identified.

Therefore, based on descriptive study results, the Measurable Success Criteria can be defined as: *Enable the possibility of producibility evaluations during multidisciplinary design according to the following requirements:*

a) Virtually to reduce development time and costly physical testing
b) Including geometrical deformation, as well as additional weld quality aspects
c) Allowing the analysis of a large set of design variants in a systematic way

The support generated in this thesis will be useful and applicable to the studied context if the support meets the three stated Success Measurable requirements.

The methods and tools within the Design for Producibility framework proposed in this thesis have served to generate adequate data and information to evaluate producibility virtually during early stages of the multidisciplinary design process. For example, in Paper D, the WCAM guidelines (created to structure expert knowledge) were combined with welding simulation to evaluate producibility. In Paper E, a Virtual Design of Experiments method was proposed to create a metamodel, i.e., a response surface based on computer experiments (simulations). In Papers F and G, a combination of different methods, such as guidelines, trigonometrical analyses, trade-off curves, response surfaces and different types of simulations, were proposed and applied to evaluate virtually the producibility of a number of variants. Therefore, the first requirement a) within the Measureable Criterion has been met.

Furthermore, the methods employed within Papers D, E, F and G have not been limited to the evaluation of geometrical deformation (distortion). These methods have also focused on additional welding producibility aspects, such as accessibility and gun rotational issues, as well as weld bead geometrical quality aspects, such as overlap and joint penetration. Therefore, the second requirement b) within the Measureable criterion has been met.

In addition, the studies presented in Papers E, F and G proved capable of analyzing the producibility of a set of design variants. For example, Paper G shows how the metamodel developed in Paper E enables prediction of the joint penetration of any design variant within the established design space. Moreover, in Paper G, the producibility of a set of 13 design variants was analyzed. Instead, before this research, analyses were conducted on single designs. Furthermore, the studies conducted in Papers F and G prescribe a systematic way of screening design variants and simultaneously building knowledge. Thus, the final requirement c) within Measureable criterion has been fulfilled.

The applicability of the support generated in this thesis has been proven through the studies in Papers F and G, in which two industrial product development contexts were selected to validate the support. The usefulness of the proposed support cannot be measured directly with the Success Criterion. However, by meeting the above stated requirements, there is a higher possibility of saving development time, increasing product quality during production and reducing cost.

5.4 EVALUATING THE QUALITY OF THE RESEARCH RESULTS

5.4.1 Evaluating the reliability and validity of the research results

As explained in Section 3.2. (see also Figure 22), the research described in this thesis has had a longitudinal evolution. The author has been working with the same research project and industrial partner in close collaboration in which successive studies have been performed contributing to the research outcome. The seven papers and eleven results items presented in this thesis and described in Chapter 4 represent the published outcome. However, the purpose of this section is to argue the validity and reliability of the research outcome in its entirety, while at the same time providing some Paper specifics whenever appropriated.

Table 8 presents a summary of the strategies adopted to ensure the realiability and validity of the research outcome.

Table 8 Strategies adoped to ensure the realiability and validty of the research outcomeTable 8

Reliability

Characteristics	*Strategies adopted*
Repeatability Reproducibility Trackability	Diary notes (reflexive journal) Documenting procedures Triangulation Checking transcripts Code Structure and Crosschecking codes Repeated measurements and replicated tests/treatments

Validity

Characteristics	*Strategies adopted*
Construct validity	Explanation building (providing definitions) Conceptualization and Operationalization
Internal validity (Consistency, Coherence and Completeness)	Prolonged engagement Case study Explanation building (rich descriptions for coherence) Triangulation of data collection and analysis Expert member checking Getting feedback from practitioners Statistical test measure Experiment replication Comparing simulation runs to physical tests
External validity (Generalizability, Transferability)	Peer review Multiple Case replication logic Rich descriptions for generalizability (transferability) Explanation building (comparing to other contexts-transferability)

5.4.1.1 Discussion upon Reliability–did we do things in the right way?

Reliability, understood as research verification, gives an answer to the question *did we do things in the right way?* Documenting as many steps as possible during the process of obtaining results is important to build reliability. Throughout this thesis, the author has been taking diary notes and collected a total of 32 notebooks in form of a reflexive journal. In these notebooks, notes were taken while collecting data during interviews, observations and also while designing studies and receiving feedback from supervisors. Mental notes, reflections, plans for future studies, as well as research outlines are also recorded in these notebooks. Each of these actions has been documented together with a date, thus classifying them along a time line.

In addition, besides the regular meetings planned with supervisors, a Steering Committee composed of supervisors and key stakeholders from industry was assigned to supervise the research every few months. For these meetings, a presentation was prepared by the author to discuss the current and future stage of the research, as well as difficulties and questions raised at that moment. A total of 35 meetings were conducted and 35 presentations recorded, which provide evidence of the progress of the research project.

Furthermore, for the particular case of interviews, a data base of people interviewed together with interview questions has been saved.

In addition, triangulation techniques have been applied with the support from three groups of Master thesis students. These three Master thesis represented an intermittent collaboration within the development of this research project (results have mainly contributed to the studies presented in Paper C and D). When working with Master thesis students, interview notes were cross-checked and commented upon and audios listened to several times when required.

In the case study performed in Paper B, Six Sigma methods were used to collect and analyze the data. The DMAIC approach within Six Sigma ensure a systematic way of working.

The model developed in Paper C has been verified by applying it to the fabrication process of two product variants (Product I and II) within the same product family. Furthermore, in Paper D, the same model supported the design and coding of the interviews and literature review carried out to find the list of producibility failure modes and connected design parameters (q_{DESIGN}).

In Paper E, welding and cutting tests have been detailed documented to build traceability and ensuring a common understanding with the welding and material departments at the industrial partner in charge of conducting the tests. Test results have also been reported in standard company documents.

Furthermore, during the welding test, each weld was made twice to handle reproducibility and repeatability issues. For the same reason, each weld cut-up was performed twice and the cut-up images were measured six times during the image processing process performed to analyze test results. In addition, the fact that welding and cutting tests were performed by professionals at the company, who employ standard procedures, reinforced reliability.

The development of the simulation model presented in Paper E was also documented. In this same study as well as in Paper G, none of the experiments within the DoE matrix were replicated. The reason is that the regression model built was based on computer experiments (welding simulations), which provide exactly the same results under the same conditions.

5.4.1.2 Discussion upon Validity–did we do the right things?

Research **validity**, i.e. *did we do the right things?*, is in part based on the long-term involvement with industry, in this case GKN Aerospace Engine Systems Sweden. By spending a prolonged time in the field, a total of seven years, the researcher has developed an in-depth understanding of the phenomena under study, which has allowed gaining insights into the industrial site and the individuals, something that gave credibility to the research findings. As stated by Creswell (2013) *"The more experience that a researcher has with participants in their settings, the more accurate or valid will be the findings"*.

Providing definitions and deconstructing theoretical concepts (or constructs) considered in this thesis, such as producibility, have provided construct validity. Conceptualizing and operationalizing have ensured validity in measuring the right things in order to be able to make generalizations about higher order concepts. For example, by looking at manufacturing variation in key characteristics (KCs) in relation with tolerance limits and by studying the relationship between the defined producibility control factors and output KCs, it has been possible to make statements about producibility.

Furthermore, the Case Study Research adopted has been beneficial in building internal validity because of the opportunity of gaining an in-depth understanding of real world phenomena.

The context in which this research is built, i.e. welded aerospace structures, presents complex settings. Therefore, providing detailed and thick descriptions has been a recurrent resource to make the results richer. This explanation building strategy has been, for example, used in Paper D to build validity with regard to the welding failures and potential causes identified.

Triangulation of both data sources and analyses has been the vital to validate research results. As discussed in Chapter 3, having adopting Mixed Method Research has enabled triangulation. In most cases, qualitative and quantitative data have been combined to build a strong and coherent justification-evidence.

Another key feature of research validity has been expert-member checking. The Action Research nature of this thesis has implied close collaboration with practitioners in the field who have helped build understanding and knowledge. Research results have continuously been checked by experts to determine accuracy of the findings. For example, in Paper D, a structured follow-up interview was conducted with key experts. In Paper E, the welding and material tests were carried out by experts at the partner company and results were commented on together. The study conducted in Paper G had a pure Action Research nature. Practitioners were involved from the design stage until the execution of the research study. The support proposed in Paper G was developed with iterative cycles of planning, action, analysis, as in Action Research.

To ensure the internal validity of the experimental results in Paper E, experiment replicas were performed. This time replication served cross-validation. In addition, the response surface-based metamodel developed was validated with a statistical measure to test model adequacy (the coefficient of determination, R^2 value).

Furthermore, the simulation model (more specifically the heat source model) proposed in Paper E was validated comparing simulation results with physical welding test results. Limitations of this study are discussed in Paper E.

The above methods ensure internal validity because they build consistency, coherence and completeness in terms of the results.

With regard to external validity, first, all appended papers have been peer-reviewed and accepted by scientific experts, thus validating the scientific contribution of the results.

Although the weak point of Case Study Research is to ensure the generalizability of the results, Yin (1994) stated that a tactic to deal with external validity in these cases is to use replication logic in multiple case studies. For example, to validate the conceptual model presented in Paper B, the model has been applied to two products within the same family (Product I and II), which constitutes a type of multiple-case study, in which the logic applied in the first has been replicated in the second case study. Paper F and G can also represent a multiple-case study, in which the methods within the Design for Producibility framework have been applied in two different product development cases, thus reinforcing transferability.

In addition, a rich description of the context, scope of this thesis, together with an explanatory comparison to other contexts will be presented below to reinforce the generalization and transferability of thesis results.

5.4.2 Further discussion upon external validity (transferability).

The intention of this subsection is to highlight the characteristics of the producibility problem and challenges faced by developing high-performance and integrated welded products and comparing them to products in other industries and to other manufacturing technologies. The objective is to draw similarities and help with generalization and transferability.

Thus, in the first part of this section, welded aerospace components are compared to other types of welded load carrying structures. In the second part, the welding process is compared to the process of additive manufacturing within the context of aerospace components.

By characterizing the problem, clarifying conditions and eliciting comparisons, the reader can draw inferences and extrapolate results to concrete cases and contexts. According to Lincoln and Guba (1985), transferability is dependent on the similarities between contexts. Thus, one needs information about both contexts to make a judgment on transferability.

Furthermore, the final part of this section provides a reflection upon the contexts to which thesis results might not be applicable.

5.4.2.1 Comparison of welded integrated performance products in aerospace industry with other industries

Welded high-performance integrated products can also be found in other industries beyond the aerospace industry. Many types of load carrying structures and components in construction machinery, mining equipment, forestry machinery, loader cranes and agriculture equipment consist of either steel plates or castings with a thickness of between [6-70mm] that are joined together mainly with welding technologies (Stenberg et al., 2017).

As with aircraft engine components, these products are subjected to variable loading during operation. Fatigue design of these welded structures imposes tough requirements on weld geometrical quality and material defects in order to ensure structural functionality. Thus, geometry and weld quality assurance become essential activities during the product realization processes of these high-performance welded components.

Integrated designs are also a common challenge during the multidisciplinary design processes of these components. Single structures with integrated geometries need to fulfill tough structural and performance requirements, while keeping weight and cost down and ensuring producibility. Thus, methods and tools for predicting geometrical and weld quality are needed in order to be proactive and avoid products that are optimized for performance but presents producibility problems.

For example, the research conducted by Ericson Öberg (2016) focuses on predicting weld quality in load carrying structures. Her research had a strong collaboration with the construction machinery industry. The challenges presented in her work are similar to those discussed in this thesis. However, Ericson focuses on tools and methods to enable weld quality predictability in production. Control charts and online quality measurement system analysis are examples of the tools and methods employed and proposed in her research (see ONWELD method in (Stenberg et al., 2017)). She also highlights the importance of setting design rules and connecting the expected fatigue properties of the weld and design limits with the welding process in order to ensure weld quality (i.e. in this thesis, connecting big-Q concept and KCs to producibility control factors, small q concept, within the welding system). The complexity once again relies on the many factors affecting the quality outcome of the welding operation and the lack of knowledge of these factors, as well as their effect on quality outcome.

Ericson Öberg (2016) work focuses mainly on factors inherent in the welding and inspection processes. Instead, the research presented in this thesis aims at providing support to assure geometrical and weld quality in the earlier stages of the product realization process. Therefore, the type of methods employed and proposed consists of welding and variation simulation, as well as predictive models which include design parameters.

Even so, some research challenges and conclusions are shared in both thesis works due to the analogies between the products in both industries. Ericson Öberg (2016) argues that an understanding of variation and an adequate and sufficient use of welding process knowledge and information are key towards predictability during both process and product development.

To conclude, the research results of this thesis could be applicable to the industries discussed above due to the strong similarities between contexts. All these products are highly constrained products for which predictive models and variation simulation are strong tools to assure and optimize welding quality during design phases. The Design for Producibility framework proposed in this thesis is suitable for these cases in which it is crucial to include producibility evaluations during the multidisciplinary design analysis and optimization processes.

5.4.2.2 Comparison of welding technologies with AM technologies in aerospace integrated products

Additive Manufacturing (AM) refers to the novel manufacturing technology that builds products (3D objects) by adding material in layers (Gibson et al., 2010). There is a great variety of AM processes that require various technologies. For example, the aerospace industry is principally benefitted by two metal AM processes: laser powder bed and electron beam deposition (O'Brien, 2019). In laser powder bed, first a metal powder is spread into a uniform layer. Second, the heat source, produced by a laser technology, fuses the shape of the desired part in the layer. The process is then repeated layer by layer. In electron beam deposition, the metal is fed either through a nozzle or as a wire directly to the heat source produced by electron beam technology.

These AM processes share great similarities with welding processes (DebRoy et al., 2018, Wei et al., 2019). Both AM and welding employ the same technologies (plasma, laser or electron beam) to produce a heat source that fuses material. In AM, the material is fused to build a 3D object from scratch. In welding, the base material of an existing part is fused (sometimes together with filler material) to join two parts together.

Therefore, materials employed in these processes undergo similar phenomena. In both welding and additive manufacturing processes, phenomena that occur are heating, melting, solidification, shrinkage and, consequently, geometrical deformation/distortion. In addition, as a result of these phenomena, the materials are exposed to residual stresses and the occurrence of defects, such as porosities, cracks, lack of fusion etc. In fact, as stated by O'Brien (2019), “a traditional metal alloy with good weldability is a candidate for AM”.

Furthermore, the advantages of introducing AM into the aerospace industry are comparable to the advantages that justify the adoption of the fabrication strategy (smaller parts welded together).

The advent of AM can enable higher flexibility and economic low volume production if compared with traditional manufacturing technologies such as casting (formative) or machining (subtractive) (Mellor et al., 2014). The design freedom provided by AM allows an efficient material allocation that together with design and topology optimization have the potential of reducing costs and increase performance in aerospace products (O'Brien, 2019) (Orme et al., 2018).

If we set aside the differences in application focus and objectives, the adoption of fabrication in aircraft engine development claims similar benefits as those of AM. As discussed in Chapter 1, substituting large cast or forged structures by designing smaller parts that must be welded has first opened up a more attractive supplier market capable of forming smaller structures. This situation has resulted in lower part cost. Second, the design space has broadened, increasing design flexibility, due to the possibility of configuring several materials and geometries.

Increased design flexibility allows weight and functional optimization, gaining product value and reducing cost (Rosen, 2007).

However, as with the adoption of fabrication, the implementation of AM is facing some challenges, which once again are related to the challenges faced by welded aerospace components, which have been presented and discussed in this thesis in the form of barriers.

As stated by (Borgue, 2019), the AM outcome depends on a wide variety of factors involving a large number of process parameters as well as materials, product geometries, etc. The process complexity added to the scarce development in AM, due to its novelty and recent emergence, leads to manufacturing limitations and unpredictable product outcomes. Although there are Design for Additive Manufacturing (DFAM) guidelines in literature (Boyer et al., 2017, Klahn et al., 2015), these guidelines may not be applicable to every product geometry and manufacturing set-up, which hinders decision-making activities, leaving inexperienced engineers with very few tools when designing for AM, as claimed by (Borgue, 2019) and (Vaneker et al, 2020).

The same barriers apply to the case of welded highly integrated performance products. A problem common to both welding and AM concerns the strong coupling between product geometry and process outcome quality. For every new product application, the outcome can be unpredictable (Dordlofva et al., 2019).

The current situation summarizes the lack of knowledge about process capabilities and lack of tools with which to predict product quality outcomes after the process during design phases.

There are also a number of challenges concerning AM simulation (Lindgren et al., 2019a, Lindgren and Lundbäck, 2018). As with computer power today, it is not possible to simulate the heat source melting point-to-point and layer-to-layer as in reality. Neither it is possible to simulate all physical phenomena that occur during the AM process (Lindgren and Lundbäck, 2018, Lindgren et al., 2019a). As in welding simulation, AM simulation also needs to consider multi-physics. The greatest modeling challenge is the estimation of defect generation, as discussed by Lindgren and Lundbäck (2018).

In summary, the needs and challenges in designing highly integrated performance products are comparable when considering both manufacturing technologies. Furthermore, both technologies experience similar physical phenomena that affect outcome quality and related causal factors. Therefore, the Design for Producibility framework proposed in this thesis, including tools to generate adequate process capability data and methods for assessing producibility and predicting the product quality outcome after manufacturing could be extrapolated to the case of additive manufactured high-performance integrated products.

5.4.2.3 Applications and contexts in which thesis results might not be valid

The concept of producibility has been adopted in this thesis for the particular application of welded high-performance integrated components to cover the gaps found in the traditional Design for Manufacturing (DFM) and Design for Assembly (DFA) theories.

Welded aircraft components are highly integrated performance products, i.e. products made of geometries closely linked to functionality. These products present tight tolerances. Thus, manufacturing variation in key product characteristics may be a critical issue.

For these products, traditional DFM and DFA methods become less applicable (refer to Paper D). Within these theories, the concept of manufacturability is understood as the easy-to-manufacture a product. Thus, DFM methods focus on reducing and simplifying part geometry and product structure (architecture) fir the objective of optimizing time and cost during production (Boothroyd et al., 2002). However, producibility criteria in highly integrated products cannot solely rely on the time and cost spent on manufacturing and assembly but rather on the quality built into the product.

Welded aerospace components are highly integrated design solutions. Slight modifications of geometry and structure (architecture) have significant effects on product performance (Raja, 2019, Forslund, 2016). The product geometry is highly integrated and coupled to a number of performance functions. In addition, for some manufacturing technologies, such as welding, geometry is also coupled to manufacturing quality outcome and cost, i.e. to producibility.

Therefore, for this type of product, the Design for Producibility framework and methods proposed in this thesis aim at foreseeing manufacturing and weld quality issues in order to design robust geometries that can mitigate manufacturing variation and satisfy all functional requirements, as defended throughout the whole thesis.

However, there are other types of manufactured products that might be complex in geometry and contain large numbers of parts for which geometry is not highly linked to product functionality. Instead, in these products, different physical modules can provide different functionalities. An example is given by Emmatty and Sarmah (2012), who present the development of a special function watch mechanism as a case study. The watch is designed in modules such as electronic module assembly, battery module assembly, date mechanism, train wheel assembly, etc. Each of the modules delivers a different function. Thus, in their case study, it is possible to apply DFA and DFM methods. DFA has been applied at the assembly level by using the minimum part criteria guidelines so that some parts in the modules were eliminated to reduce assembly difficulties and time. For example: "*The cover and three cover screws were eliminated as these components can be supported by just using a lever screw*". DFM guidelines and tools have been applied making use of existing knowledge about the capabilities of the in-house manufacturing processes at the part/component level. As a result, significant geometrical modifications were carried out to facilitate manufacture, minimize cost and avoid quality problems. For example: "*a bend in the initial design was removed that may create cracks during presswork operation*".

For this type of physical modular products, traditional DFM and DFA methods can be applied because changes in geometry, as well as architectural modifications by eliminating parts, can be performed without compromising product functionality.

In these products, the reason is that geometry is not highly coupled to either product functionality or manufacturing quality when compared to welded aircraft engine components. Thus, in these products, the objective can be to redesign the product to optimize assembly and manufacturing time and cost. There might be no need for Design for Producibility, i.e. it may not be necessary to build predictive models or simulate the effect of product geometry into manufacturing quality nor performing trade-off studies and multi-objective optimization of geometry including other performance disciplines.

6 Conclusions

In this final chapter, the summary of results and conclusions are presented. Thereafter, the direction of future research is discussed.

The research presented in this thesis has focused on producibility problems for the particular case of welded components in highly integrated performance applications. This research has aimed at contributing an understanding, as well as, providing support in the form of a framework, methods and tools to the field of Quality Engineering in general and Geometry Assurance and Variation Management in particular.

Until now, the evaluation of the effect that design concepts has on producibility criteria in the case of welded highly integrated performance aerospace components had relied to a great extent on expert judgement and physical testing. However, if the objective is to analyze a large number of geometrical design variants, this approach may become costly. The consequence is that integrated products are first evaluated and optimized towards performance, thus leaving producibility assessments in second place. In the aerospace industry, a nominal product geometry can be designed to deliver optimal aerodynamic and structural performance. However, when we fabricate this product, the product is afflicted with geometrical variation and other kinds of quality problems. Thus, at the end of the fabrication process we might obtain a product which it is not what we intended. In this type of industry, manufacturing quality problems can cause costly and time-consuming repairs and redesign loops.

Thus, the key questions with which to assess producibility during the design process of highly integrated performance products that are welded are: *Can we produce this design and at what quality level and cost?*

The thesis results support designers at assessing producibility by predicting virtually and rapidly the welding quality of a large number of product design variants during the multidisciplinary design space process of fabricated aerospace components.

To assess producibility, first we need to identify what affects producibility. Thus, the first step is mapping the fabrication process during which producibility problems may potentially occur. A producibility problem or failure occurs at manufacturing operation when the intended output quality according to specifications has not been reached.

The producibility conceptual model proposed in this thesis represents product quality creation during the fabrication process of welded aerospace components.

The model works as an information framework with which to identify and measure data about product key characteristics (KCs) that are created during the manufacturing process, carrying product quality (Q-quality), and the producibility control factors (both design and manufacturing parameters, (q-quality)) that induce variation of these key product characteristics, i.e. building quality into the product operation by operation.

During the execution of this thesis, a number of methods have been developed and employed which provide support of the following activities:

1) *Identify* what affects producibility
2) *Measure* what affects producibility to generate the pertinent process capability data
3) *Analyze* the effect of the interaction between factors that affect producibility
4) *Predict* producibility

These methods combine structured welding expertise and know-how, experimental results, welding capability data, response surface-based predictive models (including metamodels) and welding simulation data in order to manage producibility and assure manufacturing quality during design stages.

The activities connected to the methods constitute the producibility control cycle I.M.A.P. (Identify-Measure-Analyze-Predict).

The Design for Producibility framework, presented as a final contribution to this thesis, prescribes how to execute this I.M.A.P cycle within the context of multidisciplinary design and obeying Set-Based principles. In this manner, analysis loops can be performed in a systematic way to first identify all design variants that cannot be produced, i.e. unfeasible design variants. Second, to predict the quality level after fabrication of the remaining design variants. In this way, the following question can be answered: *Can we produce this design and at what quality level?*.

Modeling the effects of design and welding parameters on geometrical variation and weld quality allows predicting product geometry and welding quality. The resulted predictive models can also be amployed to conduct robustness analysis upon design and welding processes.

After the producibility analysis has been performed, the results can be evaluated in a multidisciplinary design environment to perform trade-offs between disciplines and multi-objective optimization.

With the Design for Producibility framework, producibility evaluations are no longer limited to a single geometry and study of the process parameter window. This thesis provides support of the multidisciplinary design team to analyze and predict producibility virtually and rapidly of all geometrical variants considered within the design space in order to optimize and evaluate trade-off alternatives between producibility (including the cost dimension) and performance.

The results presented in this thesis represent an advancement over traditional qualitative guidelines and expert judgments about welding difficulties towards a more quantitative approach, supporting virtual product and manufacturing development of highly integrated products.

In addition, these results represent a new way of performing DFM analysis with a manufacturing quality focus, replacing traditional DFM tools that focus purely on time or cost and vaguely consider welding. Thus, a contribution is made to Variation Management within the field of Quality Engineering. Furthermore, besides geometrical characteristics, additional quality characteristics and methods by which to evaluate their producibility have been presented, thus expanding the application of Geometry Assurance.

6.1 DIRECTIONS FOR FUTURE RESEARCH

The study of producibility has not been an easy task, in particular within the welding process system, due to the many factors interacting. The design of product and manufacturing solutions involves the selection of design parameters, materials, welding methods (equipment), process parameters and welding practices (method). All these factors control welding quality output and can also impact manufacturing cost.

These producibility control factors have been represented in an Ishikawa diagram in the producibility model (see Figure 26). Along the studies performed in this research, some of these factors have been studied in more detail than others. The effect of some of them and their interactions have been quantified (mainly for design (q_{DESIGN}) welding parameters ($q_{PROCESS}$)).

- Therefore, future work can continue along these lines, selecting new design and welding parameters and producibility responses in order to uncover new patterns.
- In addition, it will be interesting to explore the effect of different materials and welding methods. Support of welding methods selection has been initially tackled in a collaborative study presented as an additional publication (see AP4). However, there is still additional work to do. Future research can focus on studies in which different materials and welding methods can be evaluated with regard to their welding producibility. In this way, it would also be possible to support material and welding method selection.
- There are also future research possibilities within the field of robustness analysis and optimization. Building response surface-based models allows the quantification of robustness by employing, for example, Monte Carlo simulations, which can support tolerancing in later design stages.
- In this thesis, optimization has been carried out through the creation of a response surface. However, there is a wide variety of algorithms that can be employed for optimization. Future work can explore the performance of evolutionary algorithms, as well as the use of neuronal networks with which to study complex welding system.
- In the studies presented, nominal geometries have been considered when performing welding simulation. However, every process is afflicted with variation. Thus, future work can incorporate part and assembly variation as an input to welding simulation.
- There is also room for future work related to the field of welding simulation. In this research, welding simulation has been employed as an engineering method to solve context-related problems. This thesis has also presented a contribution to the development of welding simulations by proposing a new heat source model with which to simulate the effect of the laser beam inclination (refer to Paper E). Nevertheless, welding simulation can be further developed to model new context-related problems. In addition, more physics (e.g. fluid dynamics) can be incorporated into the simulation model, bridging the gap between simulation and reality, and opening up the possibilities of studying a greater number of welding quality responses.
- Ensuring producibility implies assuring the right quality levels after production and also keeping production cost. In the final article (Paper G), manufacturing cost has been included in multidisciplinary analysis. Future research can further study how different design decisions can impact producibility together with production cost in greater detail.
- The industrial implementation of thesis results was initially covered in Paper G. Additional studies can be performed on this matter: “How to implement and use the support developed in this thesis”.
- Further contributions to future research can include studies in which these thesis results are applied to other industrial contexts, for example the co-development of products produced through Additive Manufacturing technologies.

References

Abbas, M. & ElMaraghy, H. 2016. Design synthesis of machining systems using co-platforming. Journal of Manufacturing Systems, 41, 299-313.

Aderiani, A. R. 2019. Improving geometrical quality by individualizing the assembly process. Chalmers Tekniska Hogskola (Sweden).

Ai, Y., Jiang, P., Shao, X., Li, P. & Wang, C. 2017. A three-dimensional numerical simulation model for weld characteristics analysis in fiber laser keyhole welding. International Journal of Heat and Mass Transfer, 108, 614-626.

Åkerman, M. 2018. Implementing shop floor it for industry 4.0, Chalmers University of Technology.

Alblas, A. & Wortmann, J. 2014. Function-technology platforms improve efficiency in high-tech equipment manufacturing: A case study in complex products and systems (cops). International Journal of Operations & Production Management, 34, 447-476.

Ali, F., Tzanidakis, K., Goulos, I., Pachidis, V. & d'Ippolito, R. 2015. Design space exploration and optimization of conceptual rotorcraft powerplants. Journal of Engineering for Gas Turbines and Power, 137, 121701.

Almefelt, L. 2005. Requirements-driven product innovation: Methods and tools reflecting industrial needs. DOCTOR OF PHILOSOPHY, CHALMERS UNIVERSITY OF TECHNOLOGY.

Andreasen, M. & Hein, L. 1987. Integrated product development. Bedford, UK: IFS Publications Ltd.

Andreasen, M. M. 1980. Machine design methods based on a systematic approach—contribution to a design theory. Dissertation, Department of Machine Design, Lund University, Sweden.

Andreasen, M. M. The theory of domains. Workshop on understanding function and function-to-form evolution, University of Cambridge, 1992.

Andreasen, M. M., Kähler, S. & Lund, T. 1983. Design for assembly, IFS.

Attri, R. & Grover, S. 2012. A comparison of production system life cycle models. Frontiers of Mechanical Engineering, 7, 305-311.

Benyounis, K. & Olabi, A.-G. 2008. Optimization of different welding processes using statistical and numerical approaches–a reference guide. Advances in engineering software, 39, 483-496.

Benyounis, K., Olabi, A. & Hashmi, M. 2005. Effect of laser welding parameters on the heat input and weld-bead profile. Journal of Materials Processing Technology, 164, 978-985.

Blessing, L. T. & Chakrabarti, A. 2009. Drm, a design research methodology, Springer Science & Business Media.

Boeing 2019. Boeing commercial market outlook: 2019-2038. https://www.boeing.com/resources/boeingdotcom/commercial/market/commercial-market-outlook/assets/downloads/cmo-2019-report-final.pdf.

Booker, J., Swift, K. & Brown, N. 2005. Designing for assembly quality: Strategies, guidelines and techniques. Journal of Engineering design, 16, 279-295.

Booker, J. D. 2003. Industrial practice in designing for quality. International Journal of Quality & Reliability Management, 20, 288-303.

Boothroyd, G. 1994. Product design for manufacture and assembly. Computer-Aided Design, 26, 505-520.

Boothroyd, G. & Dewhurst, P. 1987. Product design for assembly, Boothroyd Dewhurst Incorporated.

Boothroyd, G., Dewhurst, P. & Knight, W. A. 2002. Product design for manufacture and assembly, New York, Marcel Dekker, Inc.

Boothroyd, G. & Radovanovic, P. 1989. Estimating the cost of machined components during the conceptual design of a product. CIRP Annals-Manufacturing Technology, 38**,** 157-160.

Borgue, O. 2019. Modelling the integration of additive manufacturing technologies in design of space components. Licentiate, Chalmers University of Technology.

Borgue, O., Muller, J., Panarotto, M. & Isaksson, O. 2018. Function modelling and constraints replacement to support design for additive manufacturing of satellite components. DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th-17th August 2018.

Boschert, S. & Rosen, R. 2016. Digital twin—the simulation aspect. Mechatronic futures. Springer.

Boyer, J., Seepersad, C., Simpson, T. W., Williams, C. B. & Witherell, P. 2017. Designing for additive manufacturing recent advances in design for additive manufacturing. Journal of Mechanical Design, Transactions of the ASME, 139**,** 100901.

Bralla, J. G. 1999. Design for manufacturability handbook, McGraw-Hill.

Bryman, A. & Bell, E. 2015. Business research methods, Oxford University Press, USA.

Buur, J. 1990. A theoretical approach to mechatronics design. Technical University of Denmark (DTU).

Caiazzo, F., Alfieri, V., Sergi, V., Schipani, A. & Cinque, S. 2013. Dissimilar autogenous disk-laser welding of haynes 188 and inconel 718 superalloys for aerospace applications. The International Journal of Advanced Manufacturing Technology, 68**,** 1809-1820.

Casalino, G. & Minutolo, F. M. C. 2004. A model for evaluation of laser welding efficiency and quality using an artificial neural network and fuzzy logic. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218**,** 641-646.

Chowdhury, S. 2002. Design for six sigma, Financial Times Prentice Hall.

CleanSky. 2019. Cleansky [Online]. Available: http://www.cleansky.eu/publications [Accessed].

Cook, T. D., Campbell, D. T. & Day, A. 1979. Quasi-experimentation: Design & analysis issues for field settings, Houghton Mifflin Boston.

Coughlan, P. & Coghlan, D. 2002. Action research for operations management. International journal of operations & production management, 22**,** 220-240.

Creswell, J. W. 2013. Research design: Qualitative, quantitative, and mixed methods approaches, Sage publications.

Creswell, J. W. & Clark, V. L. P. 2011. Designing and conducting mixed methods research, SAGE publications.

Creveling, C. M., Slutsky, J. & Antis, D. 2002. Design for six sigma in technology and product development, Prentice Hall Professional.

Dagman, J., Karlsson, M. & Wikström, L. 2010. Investigating the haptic aspects of verbalised product experiences. International Journal of Design, 4.

Dantan, J., Hassan, A., Etienne, A., Siadat, A. & Martin, P. 2008. Information modeling for variation management during the product and manufacturing process design. International Journal on Interactive Design and Manufacturing (IJIDeM), 2**,** 107-118.

Das, S. & Kanchanapiboon, A. 2011. A multi-criteria model for evaluating design for manufacturability. International Journal of Production Research, 49, 1197-1217.

Das, S. K., Datla, V. & Gami, S. 2000. Dfqm-an approach for improving the quality of assembled products. International Journal of Production Research, 38, 457-477.

De Mast, J. & Trip, A. 2007. Exploratory data analysis in quality-improvement projects. Journal of Quality Technology, 39, 301.

DebRoy, T., Wei, H., Zuback, J., Mukherjee, T., Elmer, J., Milewski, J., Beese, A. M., Wilson-Heid, A., De, A. & Zhang, W. 2018. Additive manufacturing of metallic components–process, structure and properties. Progress in Materials Science, 92, 112-224.

Dewhurst, P. 1987. Computer-aided assessment of injection molding cost-a tool for dfa analyses. Report 24Dep. Industrial & Manufacturing Engineering, University of Rhode Island, USA.

Dewhurst, P. & Blum, C. 1989. Supporting analyses for the economic assessment of diecasting in product design. CIRP Annals-Manufacturing Technology, 38, 161-164.

Dordlofva, C., Borgue, O., Panarotto, M. & Isaksson, O. Drivers and guidelines in design for qualification using additive manufacturing in space applications. Proceedings of the Design Society: International Conference on Engineering Design, 2019. Cambridge University Press, 729-738.

Drexler, K. E. 2013. Radical abundance: How a revolution in nanotechnology will change civilization, Public Affairs.

Ebro, M. & Howard, T. J. 2016. Robust design principles for reducing variation in functional performance. Journal of Engineering Design, 27, 75-92.

Eckert, C. M., Stacey, M. & Clarkson, P. 2003. The spiral of applied research: A methodological view on integrated design research.

Elgh, F. 2007. Computer-supported design for producibility: Principles and models for system realisation and utilisation.

Elgh, F. & Cederfeldt, M. 2008. Cost-based producibility assessment: Analysis and synthesis approaches through design automation. Journal of Engineering Design, 19, 113-130.

Emmatty, F. J. & Sarmah, S. 2012. Modular product development through platform-based design and dfma. Journal of Engineering Design, 23, 696-714.

Ericson Öberg, A. 2016. Predictability – an enabler of weld production development. Chalmers University of Technology

Etienne, A., Mirdamadi, S., Mohammadi, M., Malmiry, R. B., Antoine, J.-F., Siadat, A., Dantan, J.-Y., Tavakkoli, R. & Martin, P. 2016. Cost engineering for variation management during the product and process development. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-12.

Flyvbjerg, B. 2006. Five misunderstandings about case-study research. Qualitative inquiry, 12, 219-245.

Forslund, A. 2016. Uncertainty and robustness in aerospace structures. Chalmers University of Technology.

Forslund, A., Lorin, S., Madrid, J., Lööf, J., Lindkvist, L. & Söderberg, R. 2017a. Fatigue life optimization of welded aerospace structures using permutation genetic algorithms. SAE International Journal of Aerospace.

Forslund, A., Madrid, J., Isaksson, O., Frey, D. & Söderberg, R. 2017b. Evaluating how functional performance in aerospace components is affected by geometric variation. SAE International Journal of Aerospace.

Forslund, A., Madrid, J., Söderberg, R., Isaksson, O., Lööf, J. & Frey, D. 2018. Evaluating how functional performance in aerospace components is affected by geometric variation. SAE International

Journal of Aerospace, 11.

George, M., Maxey, J., Rowlands, D. & Upton, M. 2004. The lean six sigma pocket toolbook: A quick reference guide to nearly 100 tools for improving quality and speed, McGraw-Hill Education.

Gibson, I., Rosen, D. W. & Stucker, B. 2010. Introduction and basic principles. Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing. Boston, MA: Springer US.

Given, L. M. 2008. The sage encyclopedia of qualitative research methods, Sage Publications.

Goh, Y. M., McMahon, C. & Booker, J. 2009. Improved utility and application of probabilistic methods for reliable mechanical design. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 223, 199-214.

Goldak, J. A. & Akhlaghi, M. 2006. Computational welding mechanics, Springer Science & Business Media.

Goos, P. & Jones, B. 2011. Optimal design of experiments: A case study approach, John Wiley & Sons.

Hammersberg, P. & Olsson, H. Proactive control of weld dimensions in robotised mag welding. Proceedings of the second Swedish conference on design and fabrication of welded structures, 2013.

Harik, R. F. & Sahmrani, N. 2010. Dfma+, a quantitative dfma methodology. Computer-Aided Design and Applications, 7, 701-709.

Hasenkamp, T. 2010. Engineering design for six sigma—a systematic approach. Quality and Reliability Engineering International, 26, 317-324.

Hasenkamp, T., Arvidsson, M. & Gremyr, I. 2009. A review of practices for robust design methodology. Journal of Engineering Design, 20, 645-657.

Heikkinen, T., Stolt, R. & Elgh, F. 2020. Incorporating design for additive manufacturing in multidisciplinary design automation–challenges identified. Computer-Aided Design and Applications, 17, 936-947.

Henderson, K. M. & Evans, J. R. 2000. Successful implementation of six sigma: Benchmarking general electric company. Benchmarking: An International Journal, 7, 260-282.

Hermann, M., Pentek, T. & Otto, B. Design principles for industrie 4.0 scenarios. System Sciences (HICSS), 2016 49th Hawaii International Conference on, 2016. IEEE, 3928-3937.

Hernando, I., Arrizubieta, J., Lamikiz, A. & Ukar, E. 2018. Numerical model for predicting bead geometry and microstructure in laser beam welding of inconel 718 sheets. Metals, 8, 536.

Howard, T. J., Eifler, T., Pedersen, S. N., Göhler, S. M., Boorla, S. M. & Christensen, M. 2017. The variation management framework (vmf): A unifying graphical representation of robust design. Quality Engineering, 1-10.

Hubka, V. & Eder, W. E. 1988. Theory of technical systems : A total concept theory for engineering design, Berlin Springer-Verlag.

Hubka, V. & Eder, W. E. 1996. Design science: Introduction to needs, scope and organization of engineering design knowledge, Springer.

Ibrahim, I. H. & Chassapis, C. 2016. An interactive variation risk management environment to assess the risk of manufacturing variations. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-12.

Isaksson, O. A generative modeling approach to engineering design. DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm, 2003.

Jenney, C. L. & O'Brien, A. 2001. Welding handbook, volume 1 - welding science and technology (9th edition). American welding society (aws).

Jensen, T. 1999. Functional modelling in a design support system, Department of control and engineering design, Technical University of Denmark.

Johannesson, H. & Söderberg, R. 2000. Structure and matrix models for tolerance analysis from configuration to detail design. Research in engineering design, 12, 112-125.

Johansson, P., Chakhunashvili, A., Barone, S. & Bergman, B. 2006. Variation mode and effect analysis: A practical tool for quality improvement. Quality and reliability engineering international, 22, 865-876.

Jonsson, B., Samuelsson, J. & Marquis, G. 2011. Development of weld quality criteria based on fatigue performance. Welding in the World, 55, 79-88.

Juran, J. M. & Godfrey, A. B. 1999. Juran's quality handbook, McGraw Hill.

Kanigalpula, P., Pratihar, D., Jha, M., Derose, J., Bapat, A. & Pal, A. R. 2016. Experimental investigations, input-output modeling and optimization for electron beam welding of cu-cr-zr alloy plates. The International Journal of Advanced Manufacturing Technology, 85, 711-726.

Kazemi, K. & Goldak, J. A. 2009. Numerical simulation of laser full penetration welding. Computational Materials Science, 44, 841-849.

Kellari, D., Crawley, E. F. & Cameron, B. G. 2017. Influence of technology trends on future aircraft architecture. Journal of Aircraft, 54, 2213-2227.

Klahn, C., Leutenecker, B. & Meboldt, M. 2015. Design strategies for the process of additive manufacturing. Procedia CIRP, 36, 230-235.

Koch, P., Yang, R.-J. & Gu, L. 2004. Design for six sigma through robust optimization. Structural and Multidisciplinary Optimization, 26, 235-248.

Kumar, N., Mukherjee, M. & Bandyopadhyay, A. 2017. Study on laser welding of austenitic stainless steel by varying incident angle of pulsed laser beam. Optics & Laser Technology, 94, 296-309.

Landahl, J. 2018. Platform design for producibility: Early-stage modeling and assessment support.

Landahl, J., Madrid, J., Levandowski, C., Johannesson, H., Söderberg, R. & Isaksson, O. Mediating constraints across design and manufacturing using platform-based manufacturing operations. DS 87-6 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 6: Design Information and Knowledge, Vancouver, Canada, 21-25.08. 2017, 2017.

LeBacq, C., Brechet, Y., Shercliff, H., Jeggy, T. & Salvo, L. 2002. Selection of joining methods in mechanical design. Materials & design, 23, 405-416.

Lee, J. J., Lukachko, S. P., Waitz, I. A. & Schafer, A. 2001. Historical and future trends in aircraft performance, cost, and emissions. Annual Review of Energy and the Environment, 26, 167-200.

Lee, W.-S., Grosh, D. L., Tillman, F. A. & Lie, C. H. 1985. Fault tree analysis, methods, and applications — a review. IEEE transactions on reliability, 34, 194-203.

Levandowski, C. 2014. Platform lifecycle support using set-based concurrent engineering, Chalmers University of Technology.

Lienert, T. J., Babu, S. S., Siewert, T. A. & Acoff, V. L. Fundamentals of weld modeling. Asm handbook, volume 06a - welding fundamentals and processes. ASM International.

Lincoln, Y. S. & Guba, E. G. 1985. Naturalistic inquiry (vol. 75). Sage Thousand Oaks, CA.

Lindgren, L.-E. 2014. Computational welding mechanics, Elsevier.

Lindgren, L.-E. & Lundbäck, A. 2018. Approaches in computational welding mechanics applied to additive manufacturing: Review and outlook. Comptes Rendus Mécanique, 346, 1033-1042.

Lindgren, L.-E., Lundbäck, A., Fisk, M. & Draxler, J. 2019a. Modelling additive manufacturing of superalloys. Procedia Manufacturing, 35, 252-258.

Lindgren, L.-E., Lundbäck, A. & Malmelöv, A. 2019b. Thermal stresses and computational welding mechanics. Journal of Thermal Stresses, 42, 107-121.

Lorin, S. 2014. Increased precision in variation simulation by considering effects from temperature and heat, Chalmers University of Technology.

Madrid, J. 2012. Dfm-concept cost evaluation model for fabricated components at volvo aero.

Madrid, J., Forslund, A., Söderberg, R., Wärmefjord, K., Hoffenson, S., Vallhagen, J. & Andersson, P. 2017. A welding capability assessment method (wcam) to support multidisciplinary design of aircraft structures. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-19.

Madrid, J., Söderberg, R., Vallhagen, J. & Wärmefjord, K. 2016. Development of a conceptual framework to assess producibility for fabricated aerospace components. Procedia CIRP, 41, 681-686.

Madrid, J. V., Johan; Söderberg Rikard; Wärmefjord Kristina 2016. Enabling reuse of inspection data to support robust design: A case in the aerospace industry. 14th CIRP Conference on Computer Aided Tolerancing (CAT).

Manonmani, K., Murugan, N. & Buvanasekaran, G. 2007. Effects of process parameters on the bead geometry of laser beam butt welded stainless steel sheets. The International Journal of Advanced Manufacturing Technology, 32, 1125-1133.

Maropoulos, P., Yao, Z., Bradley, H. & Paramor, K. 2000. An integrated design and planning environment for welding: Part 1: Product modelling. Journal of Materials Processing Technology, 107, 3-8.

Maropoulos, P. G. & Ceglarek, D. 2010. Design verification and validation in product lifecycle. CIRP Annals-Manufacturing Technology, 59, 740-759.

Maxwell, J. A. 2012. Qualitative research design: An interactive approach, Sage publications.

Mellor, S., Hao, L. & Zhang, D. 2014. Additive manufacturing: A framework for implementation. International Journal of Production Economics, 149, 194-201.

Meyer, M. H., Osiyevskyy, O., Libaers, D. & van Hugten, M. 2018. Does product platforming pay off? Journal of Product Innovation Management, 35, 66-87.

Michaelis, M. T. 2013. Co-development of products and manufacturing systems using integrated platform models, Chalmers University of Technology.

Miles, B. 1989. Design for assembly—a key element within design for manufacture. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 203, 29-38.

Montgomery, D. C. 2017. Design and analysis of experiments, John wiley & sons.

Mørup, M. 1993. Design for quality, Techn. University of Denmark.

Müller, J. R. 2018. Towards automated conceptual design space exploration. Licentiate, Chalmers University of Technology.

Nagaraju, U., Gowd, G. H. & Vardan, T. V. 2017. An integrated approach for optimization of pulsed nd: Yag laser beam welding process. Materials Today: Proceedings, 5, 7991-8000.

Nagesh, D. S. & Datta, G. L. 2002. Prediction of weld bead geometry and penetration in shielded metal-arc welding using artificial neural networks. Journal of Materials Processing Technology, 123, 303-312.

NFFP 2019. Innovair a nationellt flygtekniskt forskningsprogram (nffp).

O'Brien, M. J. 2019. Development and qualification of additively manufactured parts for space. Optical Engineering, 58, 010801.

Olson, D. L. 1993. Asm handbook: Welding, brazing, and soldering, Asm Intl.

Orme, M., Madera, I., Gschweitl, M. & Ferrari, M. 2018. Topology optimization for additive manufacturing as an enabler for light weight flight hardware. Designs, 2, 51.

Pahkamaa, A., Wärmefjord, K., Karlsson, L., Söderberg, R. & Goldak, J. 2012. Combining variation simulation with welding simulation for prediction of deformation and variation of a final assembly. Journal of Computing and Information Science in Engineering, 12, 021002.

Pahl, G. & Beitz, W. 1996. Engineering design: A systematic approach, London, Springer-Verlag.

Phadke, M. S. 1989. Quality engineering using robust design, Prentice Hall.

Poli, C. 2001. Design for manufacturing: A structured approach, Butterworth-Heinemann.

Pronzato, L. & Müller, W. G. 2012. Design of computer experiments: Space filling and beyond. Statistics and Computing, 22, 681-701.

Ragsdell, G. 2009. Participatory action research: A winning strategy for km. Journal of Knowledge Management, 13, 564-576.

Raja, V. 2019. On the design of functionally integrated aero-engine structures: Modeling and evaluation methods for architecture and complexity. Doctoral thesis, Chalmers University of Technology.

RD&T 2009. Rd&t software manual. . Mölndal.

Reinman, G., Ayer, T., Davan, T., Devore, M., Finley, S., Glanovsky, J., Gray, L., Hall, B., Jones, C. & Learned, A. 2012. Design for variation. Quality Engineering, 24, 317-345.

Rönnbäck, A. Ö. & Isaksson, O. Product development challenges for space sub-system manufacturers. 15th International Design Conference-Design 2018, Dubrovnik, Croatia, May, 21-24 2018, 2018. Faculty of Mechanical Engineering and Naval Architecture, 1937-1944.

Roozenburg, N. F. & Eekels, J. 1995. Product design: Fundamentals and methods, Wiley Chichester.

Rosen, D. W. Design for additive manufacturing: A method to explore unexplored regions of the design space. Eighteenth Annual Solid Freeform Fabrication Symposium, 2007. University of Texas at Austin (freeform) Austin, TX, 402-415.

Rubinstein, R. Y. & Kroese, D. P. 2016. Simulation and the monte carlo method, John Wiley & Sons.

Runnemalm, H., Tersing, H. & Isaksson, O. 2009. Virtual manufacturing of light weight aero engine components. Proc. ISABE.

SAE, I. A. 2001. Variation management of key characteristics. Aerospace Standard.

Sandberg, M. 2007. Design for manufacturing: Methods and applications using knowledge engineering.

Sandberg, M., Tyapin, I., Kokkolaras, M., Isakasson, O., Aidanpää, J.-O. & Larsson, T. 2011. A knowledge-based master-model approach with application to rotating machinery design. Concurrent Engineering, 19, 295-305.

Sandberg, M., Tyapin, I., Kokkolaras, M., Lundbladh, A. & Isaksson, O. 2017. A knowledge-based master model approach exemplified with jet engine structural design. Computers in Industry, 85, 31-38.

Sanders, D., Chai Tan, Y., Rogers, I. & Tewkesbury, G. E. 2009. An expert system for automatic design-for-assembly. Assembly Automation, 29, 378-388.

Sandholm, L. 2000. Total quality management, Utbildningshuset/Studentlitteratur.

Sargent, R. G. Verification and validation of simulation models. Proceedings of the 2010 winter simulation conference, 2010. IEEE, 166-183.

Saxena, T. & Karsai, G. Towards a generic design space exploration framework. Computer and Information Technology (CIT), 2010 IEEE 10th International Conference on, 2010. IEEE, 1940-1947.

Schreve, K., Schuster, H. & Basson, A. 1999. Manufacturing cost estimation during design of fabricated parts. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 213, 731-735.

Schroeder, R. G., Linderman, K., Liedtke, C. & Choo, A. S. 2008. Six sigma: Definition and underlying theory. Journal of operations Management, 26, 536-554.

Shanmugam, N. S., Buvanashekaran, G. & Sankaranarayanasamy, K. 2012. Some studies on weld bead geometries for laser spot welding process using finite element analysis. Materials & Design, 34, 412-426.

Shanmugam, N. S., Buvanashekaran, G., Sankaranarayanasamy, K. & Kumar, S. R. 2010. A transient finite element simulation of the temperature and bead profiles of t-joint laser welds. Materials & design, 31, 4528-4542.

Siddaiah, A., Singh, B. & Mastanaiah, P. 2017. Prediction and optimization of weld bead geometry for electron beam welding of aisi 304 stainless steel. The International Journal of Advanced Manufacturing Technology, 89, 27-43.

Simpson, T. W. 2004. Product platform design and customization: Status and promise. Ai Edam, 18, 3-20.

Simpson, T. W., Peplinski, J., Koch, P. N. & Allen, J. K. 2001. Metamodels for computer-based engineering design: Survey and recommendations. Engineering with computers, 17, 129-150.

Slack, N., Chambers, S. & Johnston, R. 2001. Operations management, Financial Times Prentice Hall.

Smith, R. P. 1997. The historical roots of concurrent engineering fundamentals. Engineering Management, IEEE Transactions on, 44, 67-78.

Sobek, D. K., Ward, A. C. & Liker, J. K. 1999. Toyota's principles of set-based concurrent engineering. Sloan management review, 40, 67-84.

Söderberg, R. Robust design by support of cat tools. Proceedings of the ASME Design Automation Conference, September 13-16, Atlanta, GA, USA DETC98/DAC-5633, 1998.

Söderberg, R. & Johannesson, H. 1999. Tolerance chain detection by geometrical constraint based coupling analysis. Journal of Engineering Design, 10, 5-24.

Söderberg, R. & Lindkvist, L. 1999. Computer aided assembly robustness evaluation. Journal of Engineering Design, 10, 165-181.

Söderberg, R., Lindkvist, L. & Carlson, J. S. Virtual geometry assurance for effective product realization. 1st Nordic Conference on Product Lifecycle Management-NordPLM'06, Göteborg, January 25-26 2006., 2006a.

Söderberg, R., Lindkvist, L. & Dahlström, S. 2006b. Computer-aided robustness analysis for compliant assemblies. Journal of Engineering Design, 17, 411-428.

Söderberg, R., Lindkvist, L., Wärmefjord, K. & Carlson, J. S. 2016. Virtual geometry assurance process and toolbox. Procedia CIRP, 43, 3-12.

Söderberg, R., Wärmefjord, K., Carlson, J. S. & Lindkvist, L. 2017. Toward a digital twin for real-time geometry assurance in individualized production. CIRP Annals-Manufacturing Technology.

Söderberg, R., Wärmefjord, K., Madrid, J., Lorin, S., Forslund, A. & Lindkvist, L. 2018. An information and simulation framework for increased quality in welded components. CIRP Annals, 67, 165-168.

Stamatis, D. H. 2003. Failure mode and effect analysis: Fmea from theory to execution, ASQ Quality Press.

Steffenburg-Nordenström, J. & Larsson, M. Simulation of the influence of forming on residual stresses and deformations after welding and heat treatment in alloy 718. 11th World Congress on Computational Mechanics (WCCM XI) 5th European Conference on Computational Mechanics (ECCM V) 6th European Conference on Computational Fluid Dynamics (ECFD VI), 2014. 1657-1666.

Steffenburg-Nordenström, J. & Svensson, L.-E. 2017. Simulation and validation of forming, milling, welding and heat treatment of an alloy 718 component. International Journal of Materials Forming and Machining Processes (IJMFMP), 4, 15-28.

Stenberg, T., Barsoum, Z., Åstrand, E., Öberg, A. E., Schneider, C. & Hedegård, J. 2017. Quality control and assurance in fabrication of welded structures subjected to fatigue loading. Welding in the World, 61, 1003-1015.

Stevens, R., Brook, P., Jackson, K. & Arnol, S. 1998. Systems engineering coping with complexity, Great Britain, Pearson Education.

Stolt, R., André, S., Elgh, F. & Andersson, P. Manufacturability assessment in the conceptual design of aircraft engines–building knowledge and balancing trade-offs. IFIP International Conference on Product Lifecycle Management, 2015. Springer, 407-417.

Stolt, R., André, S., Elgh, F. & Andersson, P. 2017. Introducing welding manufacturability in a multidisciplinary platform for the evaluation of conceptual aircraft engine components. International Journal of Product Lifecycle Management, 10, 107-123.

Suh, N. P. 1990. The principles of design, Oxford University Press New York.

Swift, K. G. & Booker, J. D. 2003. Process selection: From design to manufacture, Butterworth-Heinemann.

Tabar, R. S., Wärmefjord, K. & Söderberg, R. 2019. A method for identification and sequence optimisation of geometry spot welds in a digital twin context. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 233, 5610-5621.

Taguchi, G. 1986. Introduction to quality engineering: Designing quality into products and processes.

Taguchi, G., Chowdhury, S. & Wu, Y. 2005. Taguchi's quality engineering handbook, Wiley.

Tannock, J. D., Balogun, O. & Hawisa, H. 2007. A variation management system supporting six sigma. Journal of Manufacturing Technology Management, 18, 561-575.

Tasalloti, H., Eskelinen, H., Kah, P. & Martikainen, J. 2016. An integrated dfma–pdm model for the design and analysis of challenging similar and dissimilar welds. Materials & Design, 89, 421-431.

Tata, M. M. & Thornton, A. C. 1999. Process capability database usage in industry: Myth vs. Reality.

Tennant, G. 2002. Design for six sigma: Launching new products and services without failure, Gower Publishing, Ltd.

Thornton, A. C. 1999. Variation risk management using modeling and simulation. Journal of Mechanical Design, 121, 297-304.

Thornton, A. C. 2004. Variation risk management: Focusing quality improvements in product development and production, John Wiley & Sons.

Tjalve, E. 1979. A short course in industrial design, Sydney-Wellington-Durban-Toronto, Elsevier.

Tuegel, E. J., Ingraffea, A. R., Eason, T. G. & Spottswood, S. M. 2011. Reengineering aircraft structural life prediction using a digital twin. International Journal of Aerospace Engineering, 2011.

Ullman, D. G. 1992. The mechanical design process, McGraw-Hill New York.

Ulrich, K. & Eppinger, S. 2003. Product design and development, McGraw-Hill/Irwin.

Vallhagen, J., Madrid, J., Söderberg, R. & Wärmefjord, K. 2013. An approach for producibility and dfm-methodology in aerospace engine component development. Procedia CIRP, 11, 151-156.

Vaneker, T., Bernard, A., Moroni, G., Gibson, I. and Zhang, Y., 2020. Design for additive manufacturing: Framework and methodology. CIRP Annals, 69(2), pp.578-599.

Wadsworth, Y. 1993. What is participatory action research?, Action Research Issues Association.

Wärmefjord, K., Söderberg, R., Ericsson, M., Appelgren, A., Lundbäck, A., Lööf, J., Lindkvist, L. & Svensson, H.-O. 2016. Welding of non-nominal geometries–physical tests. Procedia CIRP, 43, 136-141.

Wärmefjord, K., Söderberg, R. & Lindkvist, L. 2014. Form division for welded aero components in platform-based development. Journal of Aerospace Engineering, 28, 04014126.

Wärmefjord, K., Söderberg, R. & Lindkvist, L. Strategies for optimization of spot welding sequence with respect to geometrical variation in sheet metal assemblies. ASME 2010 International Mechanical Engineering Congress and Exposition, 2010. American Society of Mechanical Engineers, 569-577.

Wärmefjord, K., Söderberg, R., Schleich, B. & Wang, H. 2020. Digital twin for variation management: A general framework and identification of industrial challenges related to the implementation. Applied Sciences, 10, 3342.

Wärmefjord, K. S., R;Lindkvist, L; Lindau, B; Carlson, J.S. 2017. Inspection data to support a digital twin for geometry assurance. IMECE

Weber, C., Steinbach, M., Botta, C. & Deubel, T. Modelling of product-service systems (pss) bases on the pdd approach. DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia, 2004.

Wei, H., Bhadeshia, H., David, S. & DebRoy, T. 2019. Harnessing the scientific synergy of welding and additive manufacturing. Science and Technology of Welding and Joining, 1-6.

Wheelwright, S. & Clark, K. 1992. Revolutionising product development. Quantum Leaps in Speed, Efficiency, and Quality, The Free, NY.

Whitney, D. E. 2006. The role of key characteristics in the design of mechanical assemblies. Assembly Automation, 26, 315-322.

Whyte, W. F. E. 1991. Participatory action research, Sage Publications, Inc.

Widener, C. A., Burford, D. A. & Jurak, S. Effects of tool design and friction stir welding parameters on weld morphology in aluminum alloys. Materials Science Forum, 2010. Trans Tech Publ, 1261-1266.

Williamson, K. 2002. Research methods for students, academics and professionals: Information management and systems, Elsevier.

Wohlin, C. Second-generation systematic literature studies using snowballing. Proceedings of the 20th International Conference on Evaluation and Assessment in Software Engineering, 2016. ACM, 15.

Xu, K., Cui, H. & Li, F. 2018. Connection mechanism of molten pool during laser transmission welding of t-joint with minor gap presence. Materials, 11, 1823.

Yin, R. 1994. Case study research: Design and methods . Beverly hills. CA: Sage publishing.

Zang, T. A., Hemsch, M. J., Hilburger, M. W., Kenny, S. P., Luckring, J. M., Maghami, P., Padula, S. L. & Stroud, W. J. 2002. Needs and opportunities for uncertainty-based multidisciplinary design methods for aerospace vehicles.

Zheng, L., McMahon, C. A., Li, L., Ding, L. & Jamshidi, J. 2008. Key characteristics management in product lifecycle management: A survey of methodologies and practices. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 222, 989-1008.