THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Design for Manufacturing and Producibility in Fabricated Aerospace Structures

Enabling producibility assessments in 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 the methodology envisioned to enable producibility assessments in multidisciplinary design —as discussed throughout the thesis.

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To Myself

Abstract

Aircraft component suppliers must adopt new design strategies in order to absorb market growth and become more competitive at the same time as they satisfy environmental demands. To deal with this situation, weight reduction has been the key to success and have made jet engines more fuel efficient. A strategy already adopted by some engine suppliers to reduce weight has been fabrication in which small cast or forged parts are welded together into a final shape. Besides increasing the number of forming suppliers which reduces cost, another main advantage of fabrication is the 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 investigate and propose methods and tools within Design and Quality Engineering to solve producibility problems involving welded high performance structures. The research group "Robust Design and Geometry Assurance" 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 with regard to various disciplines. However, as studied in this thesis, existing methods and tools 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 produce process capability data that can be reused in future projects.

To fulfill that need, this thesis presents a producibility model to represent the fabrication process in order to understand how variation is originated and propagated. With this representation at hand, this thesis builds on the Welding Capability Assessment Method (WCAM). The WCAM is tool with which to support systematic identification and assessment of design issues related to product geometry critical to the welding process. Within this method, a list of potential failure modes during welding is connected to specific design parameters. Once the critical design parameters have been identified, quantitative methods are proposed to calculate tolerances to reduce the likelihood of welding failures.

Combinations of specialized information about welding problems, know-how, inspection and simulation data have been used to evaluate the welding capabilities of a number of product geometries. Patterns and engineering rules can be extracted by combining sources of data, both qualitative and quantitative. With WCAM, evaluations are no longer limited to a single geometry and the study of the process parameter window. Instead, the welding capability space, meaning all geometrical variants that fulfill manufacturing quality, is assessed. This information can be used to perform optimization and evaluate trade-off alternatives in terms of producibility during design space exploration and analysis, thus supporting the multidisciplinary design process.

Keywords: Variation Management, Process Capability Data, DFM, Producibility, Welding.

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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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Sincerely,
Julia Madrid
Gothenburg, Sweden, January 2018

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., 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 C
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 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

Work Distribution

Paper A
Vallhagen and Madrid outlined the concept and main ideas in the paper. With close supervision from Vallhagen, Söderberg and Wärmefjord, Madrid carried out the investigations at the industrial site. 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 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 C
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 D
Madrid outlined the concept with support of Forslund, Södeberg, Wärmefjord and Hoffenson. Madrid performed the literature review and the investigations, on which Söderberg, Hoffeson and Vallhagen provided support with comments and feedback. Forslund contributed to the Case Study and created the CAD and meshed models to be used in the welding simulations, which were performed at the industrial partner. Wärmefjord supervised the welding simulation analysis. Vallhagen supervised the “DFA and DFM” Section. Andersson contributed by writing and supervising the “Design Space Exploration in Multidisciplinary Design (MDD)” Section. Madrid wrote the paper. All authors contributed by reviewing the paper.

Additional Publications

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.

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 Knowledge, Vancouver, Canada, 21-25.08. 2017.

Forslund, A., Madrid, J., Isaksson, O., Frey, D; Söderberg, R. (2017). Evaluating How Functional Performance in Aerospace Components is Affected by Geometric Variation. SAE International Journal of Aerospace (*accepted*).

Forslund, A., Lorin, S., Madrid, J., Lööf, J., Lindkvist, L., Söderberg, R. (2017). Fatigue Life Optimization of Welded Aerospace Structures Using Permutation Genetic Algorithms. SAE International Journal of Aerospace (*accepted*).

Table of Contents

List of Abbreviations

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
CTQ – Critical to Quality characteristic
DFA – Design for Assembly
DFM – Design for Manufacturing
DFQ – Design for Quality
DFSS – Design for Six Sigma
DMAIC – Design Measure Analyze Improve Control
DFV – Design for Variation
DP – Design Parameter
DRM – Design Research Methodology
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
PV – Process Variable
RDM – Robust Design Methodology
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 THE ROLE OF AEROSPACE MANUFACTURERS IN SUSTAINABLE DEVELOPMENT

Air travel demands are steadily increasing around the world. In the last several decades, the airplane has become the common means of transportation, both for working and leisure purposes. People are travelling more and more with every passing year. In fact, the number of jet airplanes in service in 2017 is expected to double over the next 20 years, as reported by Boeing (2017). Therefore, for commercial aerospace manufacturers to achieve sustainable development and assume for social, economical and also environmental responsibilities, they need strategies to cope with market growth as the same time as they keep costs and emissions under control (Lee et al., 2001). This existing conflict between industry growth and environmental impact 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 (2017) and NFFP (2017), 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. The basic idea behind fabrication is to substitute a large cast or forged structure by designing smaller parts that must be 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.

1.2 MULTIDISCIPLINARY DESIGN IN AEROSPACE STRUCTURES

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, 2016). 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 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).

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) [Ansys, Hyperworks, Siemens Advanced Simulation]. However, the assessment of manufacturing capabilities is less developed within the multidisciplinary design process. Producibility, as a property, also need to be optimized. A design optimized only from a functional perspective can be expensive or unfeasible to realize during production (Runnemalm et al., 2009). Products can be robust not only in terms of their performance and service variability (reliability concept) (Ebro and Howard, 2016), but they also need to be producible and robust in terms of their manufacturing variation (robustness concept) (Söderberg and Lindkvist, 1999).

1.3 MANUFACTURING VARIATION IN FABRICATED AEROSPACE STRUCTURES

The adoption of fabrication, small cast or forged parts welded together, has some benefits as explained above but it has also an impact on the manufacturing process. Fabricated aerospace structures, in turn, imply a more complex production solution than single structures. The number of parts increases along with the number of assembly steps. In addition, the use of welding often requires pre-operation to prepare the joint for desirable conditions and post-operation, such as heat treatment, thus increasing considerably the manufacturing operation list. If the number of processes increases, geometric 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, manufacturing variation problems are being aggravated with fabrication.

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 will lead 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 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 "Robust Design and Geometry Assurance" group within the Wingquist Laboratory of the Chalmers University of Technology in close collaboration with the aerospace industry. 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 1.

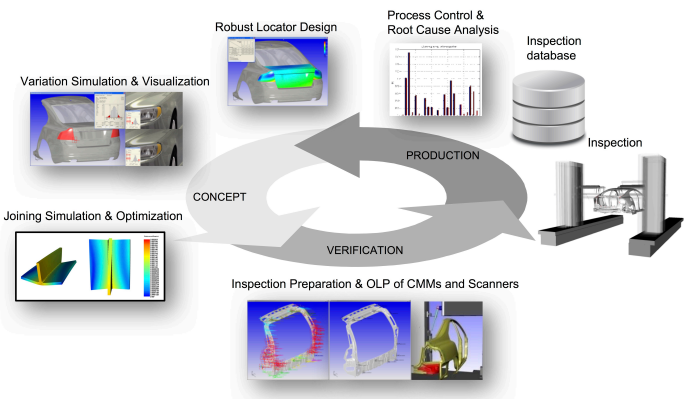

Figure 1 Virtual Geometry Assurance process and toolbox (Söderberg et al., 2016)

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

1.3.2 The need for producibility assessments in welded aerospace structures

In the case of welded aerospace structures, the degree of precision required in

manufacturing due to tight tolerance makes the effect of manufacturing variation and particularly geometric 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. At the same time, the fabrication process output is dependent on product geometry. The manufacturing outcome is also coupled to design. 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. A great deal of human work and adjustment during assembly and welding induces low levels of automation and repeatability (Sanchez-Salas et al., 2017). All above mentioned means that 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 structures, there is a need to expand the Geometry Assurance framework by adding the development of new activities to assure quality as well as new methods to assess and predict producibility. 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. Thereafter, support needs to be provided early in the design process to achieve an optimized balance of requirements, ensuring the final quality after production has been reached together with affordable total cost. All this motivates the goal of this project and the research questions presented below.

1.4 SCIENTIFIC MISSION

1.4.1 Purpose and goal

The overall purpose of this research is to enable a product realization process for fabricated aerospace structures where producibility is efficiently assessed from an early beginning.

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 requirements is optimized, hence achieving an affordable product cost while attaining a high level of quality is reached. 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 with the support of managing manufacturing variation and ensuring quality earlier during the design process of fabricated aerospace structures.

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. Both study areas represent the interaction of design-manufacturing, the first area from the perspective of design and the design process, the second area from the perspective of manufacturing and the manufacturing process. Thus, each phenomenon belongs to a different paradigm, the Design paradigm and the Manufacturing paradigm (see Figure 2).

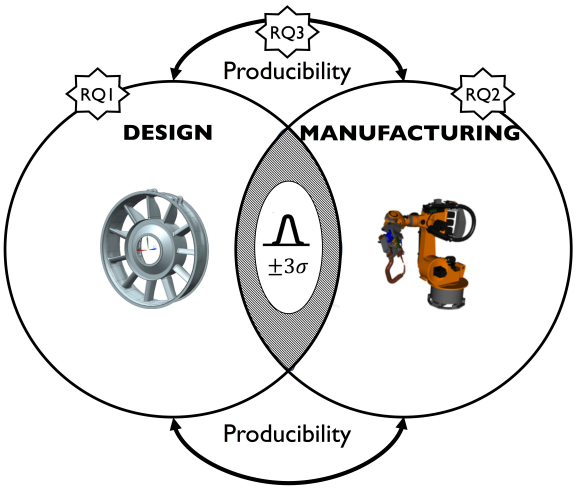

Figure 2. RQs connected to study areas. Producibility can only be considered in the design-manufacturing interaction. Manufacturing variation ($\pm 3\sigma$) is the consequence of the interaction and the effect of producibility

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 research question aims at closing the gap between the first two research questions, i.e., how the producibility problems encountered during manufacturing can be analyzed earlier during the design process. Therefore, this last question aims at closing the gap between both design and manufacturing paradigms, as illustrated in Figure 2.

RQ3: How can producibility assessments be supported during the multidisciplinary design of fabricated aerospace components?

1.4.3 Academic and industrial relevance

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

Academic 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 manufacturing 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 to contribute to Design and Quality Engineering with methods for Quality Assurance and Variation Management for the particular case of fabricated aerospace structures.

Industrial relevance—The industrial goal is to propose a framework (methods and tools) which supports designers at predicting product-production quality during the analysis phase of the design of product variants in the context of fabricated aerospace structures, as well as increasing knowledge of what controls quality in welded structures.

1.4.4 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, which is why the research is based on this context. Nevertheless, as with all research, the aim is to present results that are generally applicable to other cases, thus contributing to new academic knowledge. Within this thesis, the applicability of results is delimitated to all fabricated and assembled products with high performance in which fusion welding has been the selected means for the joining process.

In addition, as discussed by the author in the 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. Moreover, the focus of this thesis has been principally focus on quality. Cost as a concept has not been yet considered. However, to complete the study of producibility, the concept of cost needs to be incorporated into the quality achieved, an aspect is considered under Future Research.

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, building 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 and interconnects and summarizes them in order to provide a coherent body of findings discussed in subsequent chapters.
Chapter 5 discusses the results in relation to research questions, existing literature and discovered research gaps. Answers to each research question are provided and comments made regarding their implication for theory and practice. The validity of the results is also discussed based on the criteria presented in Chapter 3.
Chapter 6 presents the main conclusions of this research and the future research agenda.

2 Frame of Reference

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

The main contribution of this thesis is not to a specific scientific field but to three overlapping fields, Engineering Design, Quality Engineering and Manufacturing Engineering. The Venn diagram shown in Figure 3 and inspired by the ARC diagram (Blessing and Chakrabarti, 2009) indicates the relevant theories within each field and builds the frame of reference and area contribution of this thesis.

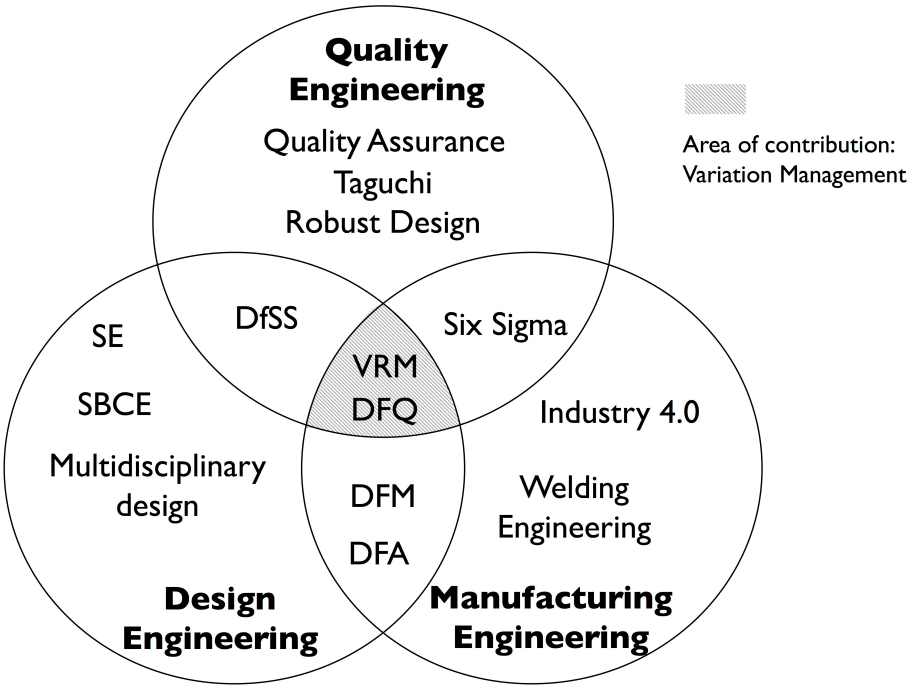

Figure 3. Venn diagram representing areas of relevance and contribution (inspired by ARC diagram)

2.1 DESIGN ENGINEERING

One part of Engineering Design research has been focusing significant attention on developing systematic methodologies for product development (Ulrich and Eppinger, 2003), (Roozenburg and Eekels, 1995), (Pahl and Beitz, 1996), (Andreasen and Hein, 1987), (Hubka and Eder, 1996, Ullman, 1992), (Ullman, 1992). Figure 4 illustrates a generic product development process, as proposed by Ulrich and Eppinger (2003), including such major activities as planning, concept development, system, design, detail design, testing and refinement, in addition to production ramp-up.

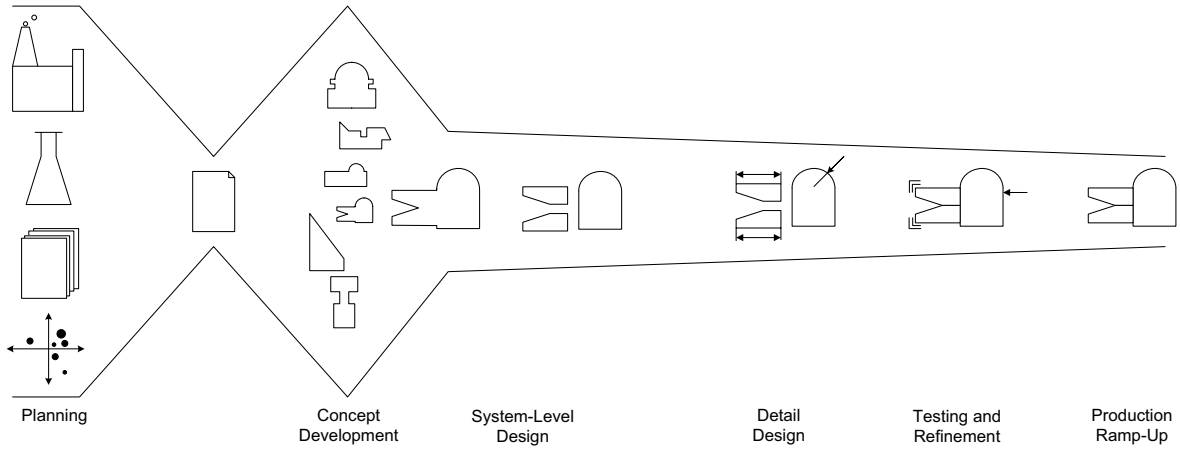

Figure 4. Generic product development process (Ulrich and Eppinger, 2003)

In a consistent fashion, the main four phases in engineering design outlined by Pahl and Beitz (1996) are: Product planning and clarifying the task, conceptual design, embodiment design and detail design. Adding to the above, a variety of design process theories has been proposed by other authors (Andreasen and Hein, 1987), (Roozenburg and Eekels, 1995). Although the different theories about the design process differ slightly they all consider Systematic Design as a framework for product development. Systematic Design prescribes a well-structured, target-oriented and sequential main workflow, in which design methods and tools can be connected to each phase. The initial point is the planning phase during which the customer and market situation are studied in order to derive a list of requirements. Based on these requirements, conceptual solutions (function and product structures) are generated, evaluated and selected for further development. During embodiment, the details of the design are being refined, evaluated and improved in an iterative process until the final design form is complete and the definitive product layout is developed. Thereafter, it is time to build prototypes to test and verify the concepts in order to purpose production ramp-up. Some of these theories advocate making the design process more integrated (Andreasen and Hein, 1987), (Prasad, 1996).

Nevertheless, the sequence of different activities and events within the process of designing is in essence the successive definition of the so-called design properties and characteristics (Tjalve, 1979), (Andreasen and Hein, 1987). It is worth mentioning and clarifying the distinction between design properties and characteristics adopted in this thesis based on (Tjalve, 1979) and (Andreasen and Hein, 1987).

The *properties* describe the product behavior and can only be determined indirectly by the choice of characteristics. Properties relate to Hubka´s and Eder´s (1996) “external properties” and to Suh´s (1990) functional requirements. Examples of product properties are weight, safety, reliability and aesthetics properties, in addition to the so-called relational properties which can only be obtained when the product considered as a system is related to another

system. For example, producibility, is a relational property emerging of the relation of both product and manufacturing systems.

On the other hand, *characteristics* define the product, describe the structure and constituents and can be determined by the designer. The characteristics are similar to the "internal properties" defined by Hubka and Eder (1996) and to what Suh (1990) called "design parameters" within Axiomatic design, which involves part structure, geometry, material and surface characteristics of a product. The design characteristics are what designers can create and manipulate directly during the design process, which in turn will define product properties and thus product functionally and quality.

The relation between characteristics and properties is established by two main activities during the design process: synthesis and analysis, as discussed more explicitly by Jensen (1999), Tjalve (1979) and Weber et al. (2004). See also Figure 5. The design process starts with the formulation of required functions and properties, which in principle make up the requirements list. During **synthesis**, product characteristics, such as structure, form, dimensions (geometry), material and surface roughness are determined based on required product properties. There exist a number of product modeling theories supporting the synthesis process, including Theory of Technical Systems (Hubka and Eder, 1988), Theory of Domains (Andreasen, 1992), Functional-means approach (Tjalve, 1979), (Andreasen, 1980) and Axiomatic design (Suh, 1990), etc.

During **analysis**, the product system is analyzed in terms of its purpose. Thus, product properties are determined or predicted based on their given product characteristics. Analysis activities can be performed via experiments or virtually through simulation tools. Along all phases of the design process, synthesis and analysis activities are performed in iterative loops until the definitive product layout has been developed.

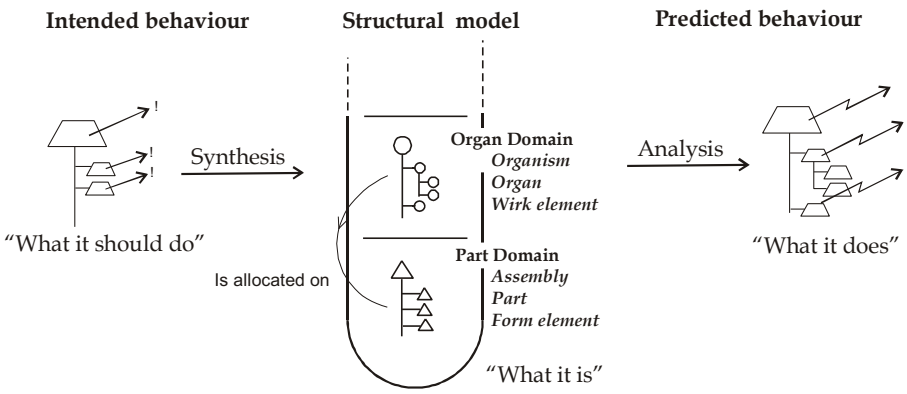

Figure 5 Synthesis and Analysis as understood by Jensen (1999)

2.1.1 Approaches to interdisciplinary 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 development are fundamental to these cases. Some of the most relevant cases will be outlined below.

2.1.1.1 Concurrent Engineering

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

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). In SE, both business and technical needs of all stakeholders should be considered for the purpose of providing a quality product that meets user needs. 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 6) 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 can be systematically analyzed using different tools at various stages during production development. There is also an opportunity to support the creative synthesis of solutions. Ideally, to achieve high producibility, both the product design and its manufacturing process need to be defined in parallel.

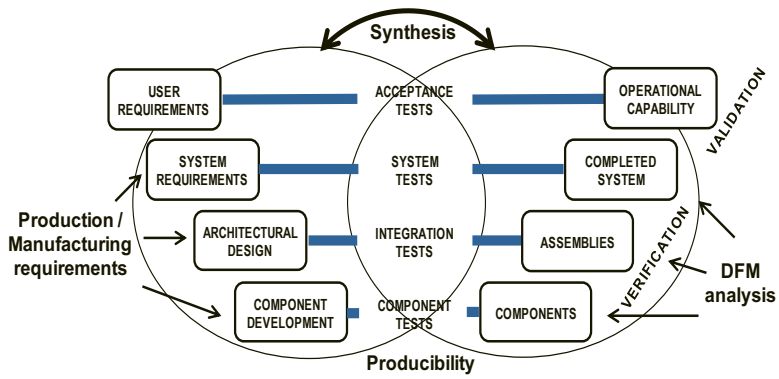

Figure 6 V model from Systems Engineering showing producibility assessment opportunities (Vallhagen et al., 2013)

2.1.1.3 Set-Based Concurrent Engineering

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.

Current research has studied how SBCE principles can support the design of product variety within the context of platform-based design in order to respond to increased market diversity and gain the benefits of mass customization (Levandowski, 2014).

Within the context of this research, Design Engineering and Manufacturing Engineering can define broad sets of feasible solutions in their respective areas. In addition, the need to deal with uncertainty during the early stages of the design process, as discussed in the Introduction, 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.

2.1.2 Design for Assembly and Design for Manufacturing

The above refers to environments and methodologies within Design Engineering in order to integrate production aspects during the design process. However, the first attempts involving methods and tools appeared in the 1960s when companies were developing guidelines to use during product design (Boothroyd, 1994). An example is the Manufacturing Produciblity Handbook published by General Electric (1960) for internal use in the U.S. Manufacturing data were accumulated in reference volumes to make them available to designers. However, these guidelines were highly product case-related. In addition, more attention was given to the design of individual parts for producibility and less attention was given to assembly. The need of more generic and systematic approaches which also focused on the assembly 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.

Within the group of qualitative methods in the field of DFA, Andreasen et al. (1983) and Pahl and Beitz (1996) developed guidelines including graphical representations of beneficial and poor practices with the intent of supporting designers in their task to create designs easy to assemble. In the field of DFM, 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. A later contribution was made by Swift and Booker (2003) and their manufacturing PRocess Information MApS, PRIMAS. All DFM guidelines reviewed were produced with mature production technologies in mind, so that commonly considered production processes were included, such as machining, injection modeling, casting or stamping. Even so, some of these 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"*.

Moving to quantitative methods, two renowned systematic methods that established the basis of DFA were 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 first step of Lucas DFA method is functional analysis. In functional analysis, parts that are critical to product performance quality are identified and classified apart from those that are not critical. Then, minimum-parts criteria are applied to the non-critical parts. Thereafter, the remaining parts are scored based on the results of handling and fitting difficulty analysis.

The DFM systematic methods emerged after the successful implementation of the systematic 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 7. The purpose of DFM methods is 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"*. The traditional DFM methods involve the assessment of part-manufacturing difficulties. Therefore, focus is placed on optimizing design for forming processes, such as casting, stamping, injection molding and machining processes. Thus, less focus is placed on welding. Within this group, cost estimation models have been developed as DFM quantitative tools to evaluate manufacturability (Boothroyd and Radovanovic, 1989), (Dewhurst, 1987), (Dewhurst and Blum, 1989). Some of these methods were feature-based evaluation tools. Cost indices were given for processing the different features using parametric models and a library of manufacturing knowledge bases. Although DFM attention has been traditionally paid to the shape-forming processes, Schreve et al. (1999) presented a DFM cost model for tack welding using a time and rate approach. However, this cost model uses a time and rate approach without focusing on output quality.

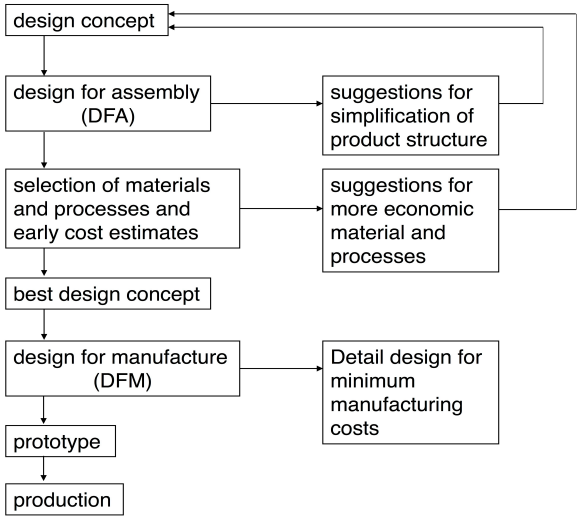

Figure 7 Steps for DFMA methodology

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 solutions). 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 8.

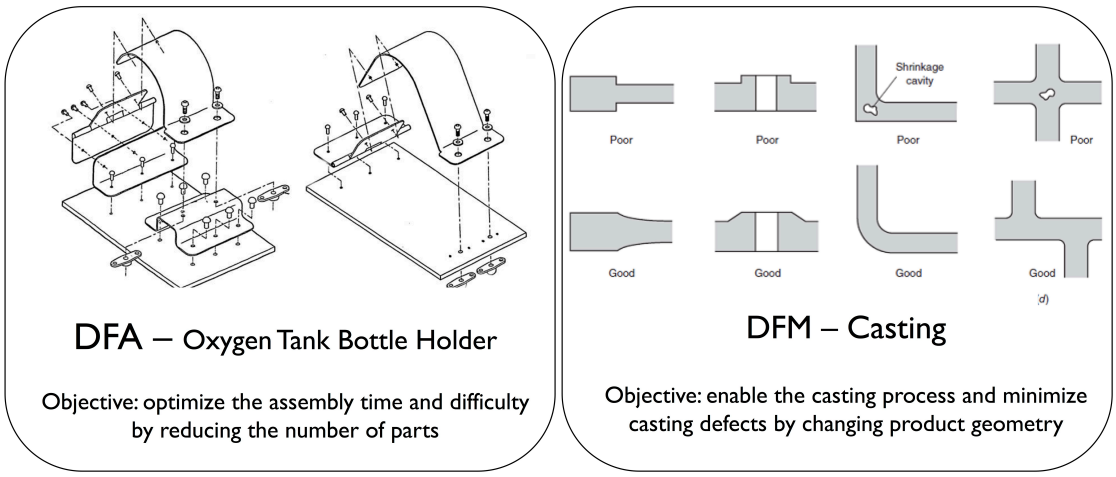

Figure 8 Typical examples of DFM and DFA applications found in literature, in which substantial geometrical and structural modifications have been applied (Boothroyd et al., 2002) (Bralla, 1999).

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 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 the welding process 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

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 he first introduced DFQ, Mørup (1993) differentiated between *big Q* and *little 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 *little q* represents the quality perceived by the internal customer, production. Later on, 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 which 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 9 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, Taguchi Robust Design, Geometry Assurance and Variation Risk Management, etc.

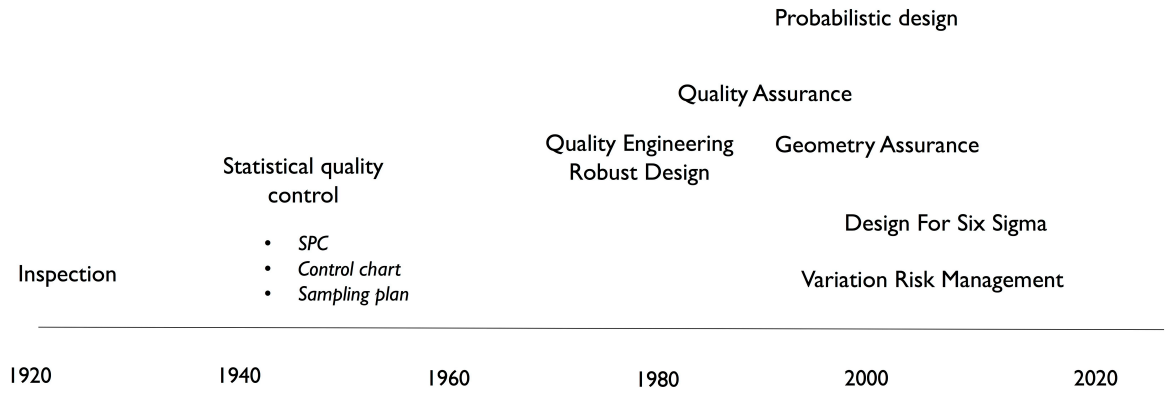

Figure 9 The historical evolution of quality control

2.2.2 Design for Six Sigma

Initially, after Motorola launched a Six Sigma program for the first time, Six Sigma tools were applied to discrete manufacturing commonly used in process improvement (Schroeder et al., 2008). Now, these tools have extended their application to nearly all tasks within the activities of an organization. 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 section 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 10). 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.

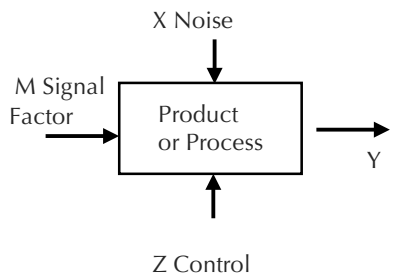

Figure 10 P-diagram (Phadke, 1989)

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 11 illustrates this procedure using the graph of a function.

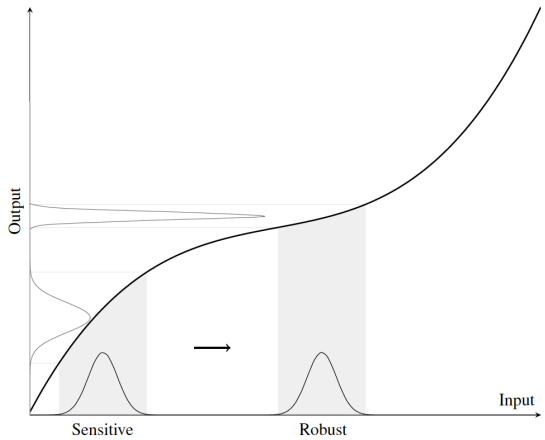

Figure 11 Robust Design illustrated using 1-dimensional function

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.

There exists a more holistic and recent 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 Figure 12. Principles relate to the question *Why*, providing the reason or rationale for working with RDM. Practices adress *What* activities need to be carried out to fulfill those principles. Tools support *How* to put these practices into action.

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)

Figure 12 Principles, practices and tools of Robust Design Methodology (Hasenkamp et al., 2009)

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). 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, 2017b).

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 geometric variation is presented by Söderberg (1998), see Figure 13.

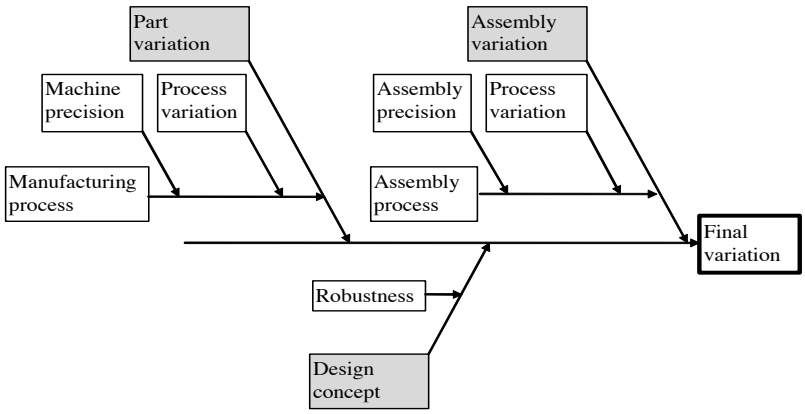

Figure 13 Contributors to final geometrical variation by (Söderberg, 1998)

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 geometric variation of the final product. Furthermore, the robustness of the design influences how variation accumulates and propagates. Thus, variation in individual parts is not the entire problem but how combinations of variation in parts and assembly robustness 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 a *Geometry Assurance* process to develop geometrically robust products. A geometrically robust design fulfills functional requirements even when the geometry is impacted by minor manufacturing variation. Therefore, *Geometry Assurance* is a set of activities and tools linked to the product development cycle in order to assure geometrical quality. Geometry assurance consists of controlling the effect of geometrical variation from the early design phases with the use of Probabilistic Design practices, through verification, preproduction and, finally, through production during which experimental data can be gathered to feed design models, see Figure 14.

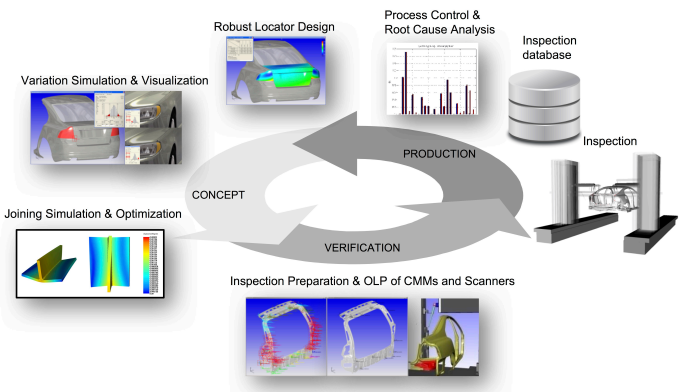

Figure 14 Virtual Geometry Assurance process and toolbox (Söderberg et al., 2016)

The tolerances that apply and how these tolerances propagate and accumulate during the assembly process to the final product is part of Tolerance Management. 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, or analytical methods (Shah et al., 2007). 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. Therefore, the concept of Key Characteristic (KC) is used nowadays both in the aerospace and other industries to focus improvement efforts only on those product features and processes that have major impact on quality and thus on customer satisfaction (Thornton, 2004), (Whitney, 2006), (Zheng et al., 2008), (SAE, 2001).

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.

Regarding the use of KCs to deal with manufacturing variation in product development, 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 is critical to customer requirements, i.e. performance quality. 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. This 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 discrete 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 industries (Madrid, 2016).

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 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 15.

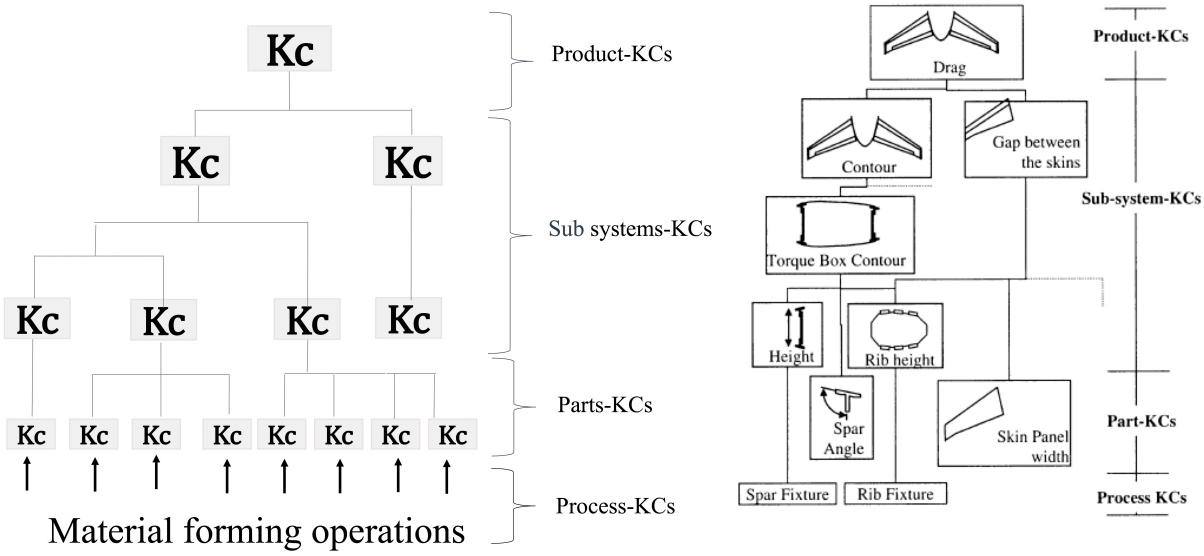

Figure 15 KC flowdown in theory and example in aerospace application as shown in (Thornton, 1999)

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.

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.

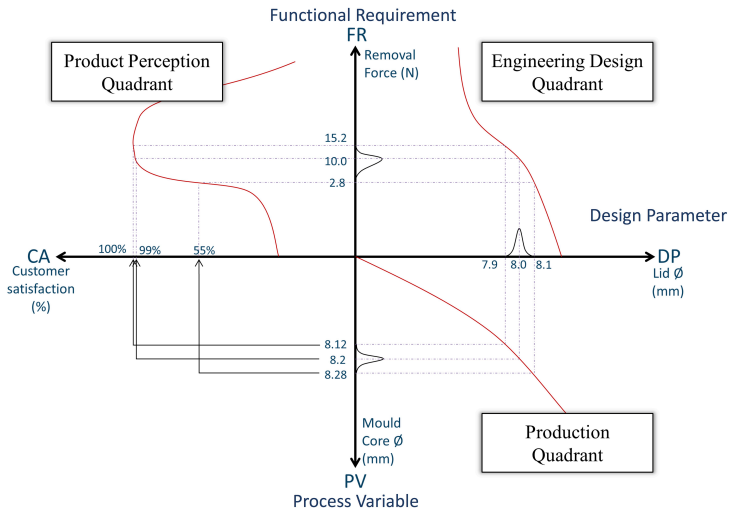

Figure 16 A Variation Management Framework (VMF) as presented by (Howard et al., 2017)

However, 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), whereas some DPs can also be contributors themselves to production variation and thus to variation in other DPs as pointed out in the Results and Discussion of this thesis.

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). In addition, Subramaniam and Ulrich (1998) presented an approach in which producibility metrics have been extracted from defect or failure analysis of the manufacturing process. Their approach focuses on producibility problems that arise due to part geometries. However, this approach only covers forming processes, such as extrusion, injection molding, casting, and machining processes, not welding. Even so, their research has provided significant inspiration to the author.

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 a Ishikawa diagram is used to identify all possible Noise Factors.

2.3 MANUFACTURING ENGINEERING

2.3.1 Manufacturing process modelling

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 (Slack et al., 2001), (Sandholm, 2000), (George et al., 2004). For example, input and output diagrams and flow charts serve as the basis for manufacturing process analysis since they enable process mapping, thus providing a useful overview of the process. In essence, this basic process modelling is helpful when setting process boundaries. 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 10, 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. TTS was developed to support engineering design of technical systems. In TTS, the product is considered to be a Technical System (TS) which executes a Transformation Process (TrfP) to fulfill a certain function. For example, a washing machine is the TS and the TrfP is the activity of cleaning the clothes. The TrfP represented within TTS works as a "black box" to which inputs in a certain state enter and from which outputs in a transformed state exist. Inputs and outputs are called operands (Od1 and Od2). In the example, dirty clothes would be the input, whereas clean clothes would be the desired output. According to TTS, the TS and other systems such as the Human System, the Information System and the Management System, will affect the transformation process (TrfP) and influence output response, manifesting variation. A model depicting a transformation system, operands and a transformation process is presented in Figure 17.

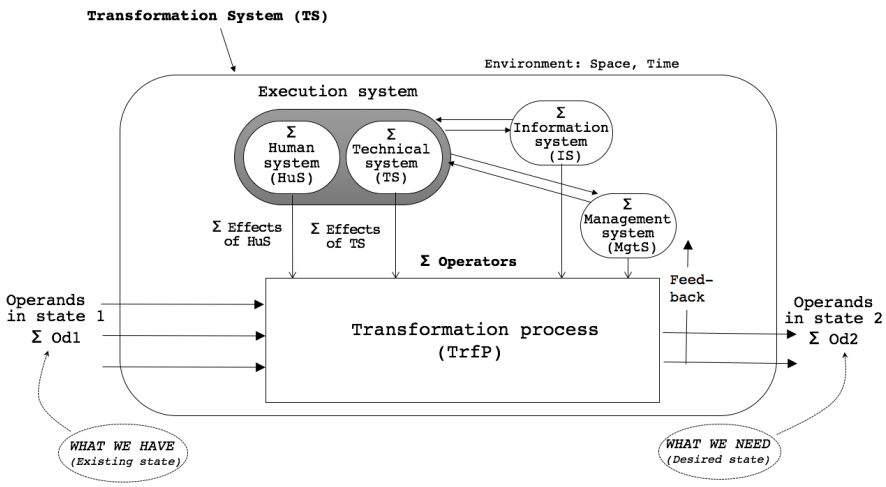

Figure 17 A model of a transformation system, redrawn from (Hubka and Eder, 1988)

In the same fashion as transformation processes can support product modeling, they can also support manufacturing process modelling. 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). 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 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, the concept of process capability (Taguchi et al., 2005). Process capability (C_p) acts as an indicator of process performance since it relates process variation, represented by 6σ, to tolerance limits (TL).

$$\text{Process capability: } C_p = \frac{TL}{\pm 3\sigma}$$

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

2.3.3 Industry 4.0 and Big Data

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. Thus, some of the current challenges lie in the creation of adequate systems that acknowledge the need for different stakeholders information and can provide the right information at the right place and at the right time.

In this context, there is an increased need for probabilistic design, variation modelling, variation analysis tools and simulations to enable Digital Twins and to virtually verify both product and production concepts (Söderberg et al., 2017). However, 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).

2.3.4 Introduction to Welding Engineering

The objective of this subsection is to introduce the reader to welding technology because it 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. 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).

Many factors control or affect the quality of the welding output, including welding process parameters, weld joint geometry, fixture designs, product form division and product geometry. Furthermore, the welding output depends on the input state, which is the result of what has happened to the product in previous operations.

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 technology. 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). All in all, welding output quality is dependent of many variables, which are 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 this process sensitive and complex. The overlaying of all these vulnerabilities leads to a small processing window in which the welds can be made without undesirable defects.

Within the field of Welding Engineering, research attention is primarily paid to understanding the process parameter window and how different welding process variables, such as welding speed, current or voltage, affect the 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, thus understanding the effect of a design or a variety of designs on weld quality has been less explored. Therefore, no support is provided on how different product geometries, constituting the design space, affect welding process output.

2.3.5 Introduction to Welding Modeling and Simulation

Can weld quality be simulated to support product design? The modeling of welding consists of three parts and their coupling as shown in Figure 18. Heat transfer, microstructure evolution and mechanical structure evolution affect each other (Goldak and Akhlaghi, 2006). The main interactions are from thermal to mechanical and microstructure and from microstructure to mechanical (see continuous lines).

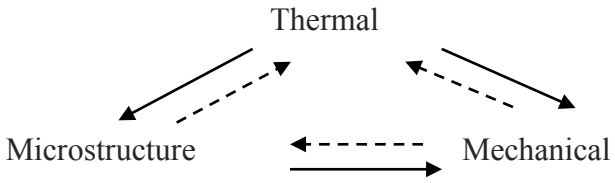

Figure 18 Coupling between mechanical, thermal and microstructure analysis. Continuous lines represent major influences while dashed lines represent minor influences. (Goldak and Akhlaghi, 2006)

As today, welding simulations are performed and verified to predict residual stresses and distortions. Thus, simulations include thermal and mechanical analyses. Nevertheless, in academia but also in industrial application, to this day, there is still a large proportion of characteristics constituting weld quality, such as the formation of metallurgical defects and weld bead geometry, that cannot be simulated. Thus, physical testing and expert judgments still play important roles (Madrid et al., 2017).

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

So, what are the possible applications of welding simulations? 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 the 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 the 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), (Forslund, 2017a). Still, the majority of welding simulation applications have been focused on supporting the design of the manufacturing rather than the product design process.

3 Research Approach

This chapter first justifies suitable frameworks for this scientific study. 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?

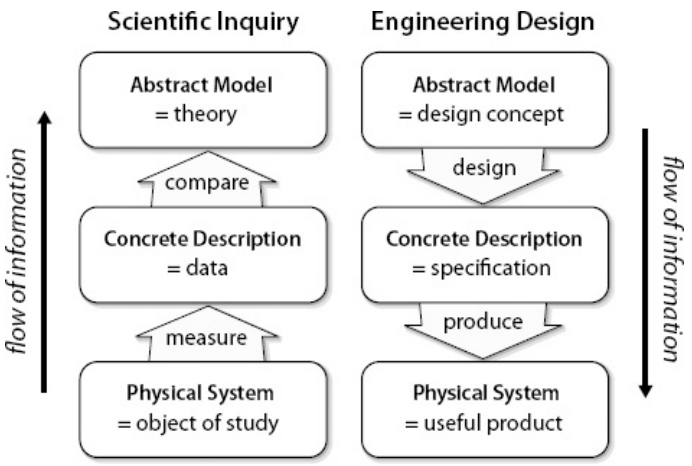

Figure 19 Scientific inquiry vs Engineering Design by (Drexler, 2013)

In his explanation about the difference between science and engineering, Drexler (2013) uses the flow of information as a differentiator. In scientific inquiry, knowledge flows from the bottom to the top, i.e., from studies and observations of specific parts, general things can be concluded. 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 and knowledge 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 confirm that the theories were correct and that new theories may be developed.

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 as the same time as practical solutions to industrial implementation are provided.

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 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 paradigm. 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 paradigms, thereby communicating knowledge between the two fields (Design and Manufacturing). In this dualism, the author has adopted a pragmatic view of the problem in which mixed research methodologies and methods has 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.

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.

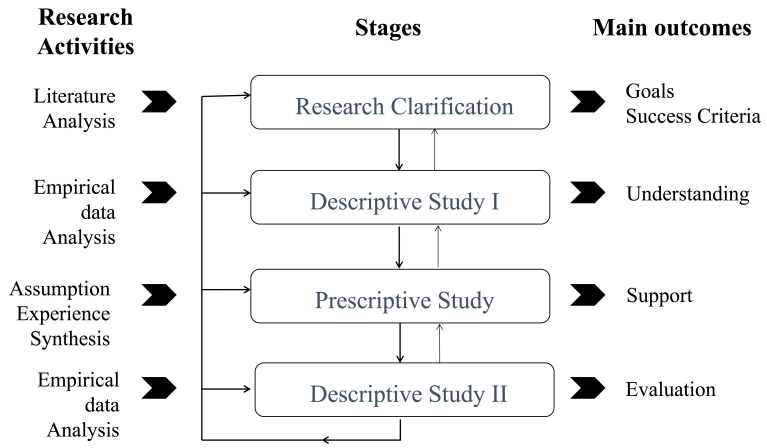

Figure 20 The DRM framework, redrawn from (Blessing and Chakrabarti, 2009)

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 been a central 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 (please see Sections 3.5, 5.2 and 5.3).

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 Design field. 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–phenomena that 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

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. That integrated whole, with its structure and connections, is represented in Figure 21.

Figure 21 illustrates a time line where a total of four different papers and their related research activities are represented. On the top level of abstraction, the research process is divided into three main stages in accordance with the Design Research Methodology (DRM). Paper A covers the Clarification Phase during which three preliminary research questions and success criteria with which to evaluate the research quality are formulated. Descriptive Study I is conducted through the studies carried out in Papers A, B and C. Finally, Paper D represents the Prescriptive Study, in which a supportive method has been formulated. The last phase of DRM, Descriptive Study II, has not yet been covered and is planned to be addressed in the final Ph.D. thesis. Thus, the main focus of this Licentiate thesis has been on acquiring a comprehensive understanding of the existing situation and phenomena studied. In addition, initial support has been proposed but needs further development and testing. Although Figure 21 illustrates a linear execution of the DRM stages, which shows coherence with the overall picture, the research work has been performed in iterative cycles.

These cycles are implicitly shown in Table 1, which indicates whether the contribution has been either descriptive or prescriptive and what study area or phenomenon has been in focus for each single paper (see Figure 2, in the Introduction). The major contribution is placed on Descriptive Study I for both study areas. There are three research questions governing this research. The first two questions have a descriptive nature, whereas the third is connected to the prescriptive study. These questions were initially formulated during the clarification phase and have been reworked in parallel ever since. 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 three research questions continuously. By a connecting line, Figure 21 shows how each paper contributes to each research question.

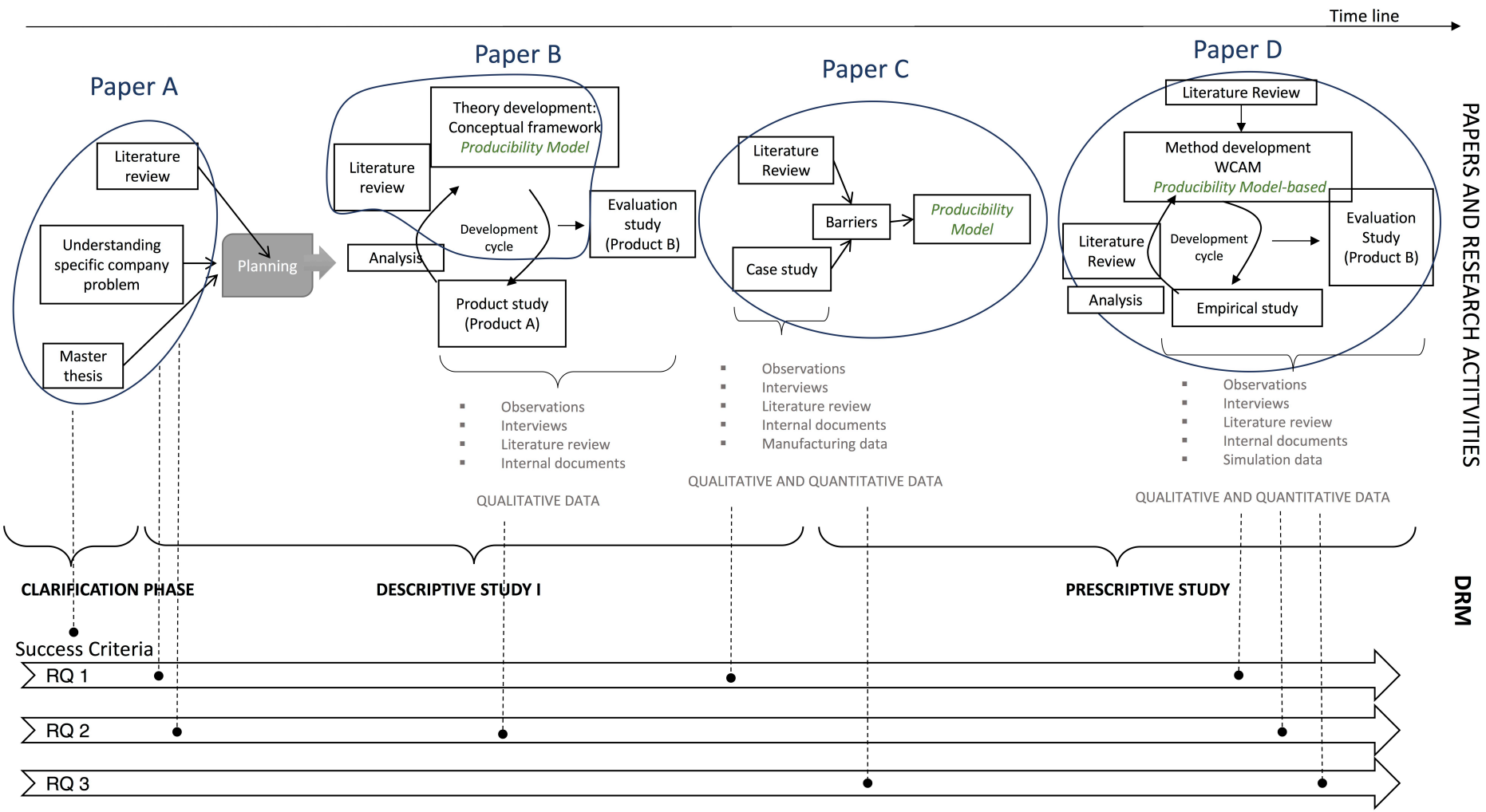

Figure 21 Applied research process

Table 1 Connections between papers, study areas, DRM phases and research questions

Results	Study Areas		Descriptive Study I		Prescriptive Study
Papers	Design	Manufacturing	RQ1	RQ2	RQ3
A	√		✈	✈	
B		√		✈	
C	√	√	✈		✈
D	√	√	✈	✈	✈

✈ strong contribution; ✈ low contribution

The research presented in this thesis has been connected to the same research project. The initial research problem, originating in the aerospace industry, has been formulated concurrently with the industrial partner. 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. The research process has a longitudinal nature, in which the various studies reflected in the different papers have been focused on the same case. Four TEC different variants have been studied to understand similarities and differences. Two of them have been selected as main cases for investigation because their fabrication process is similar and because one of the variants represents the improvement state of the other, where producibility issues were better handled (In Figure 21 represented as Product A and Product B, respectively). During the initial descriptive studies, case studies were chosen over laboratory studies with which to describe and understand the phenomena within manufacturing. The aim was to raise all possible factors affecting producibility. Moreover, a control environment could not accurately reproduce the phenomena studied, besides the high experimental cost that this would entail. In latter iterations, simulations were used as experimental studies because descriptive studies were better able to isolate the phenomena.

A more detailed description of the research activities connected to each paper is presented as follows:

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 RQ 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 area studied. This paper describes the existing situation both in academia and industry, thus contributing to the field of Design Engineering.

Paper B: Unlike Paper A, Paper B focuses on the manufacturing process as study area. It contributes to the description and modelling 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 has been developed through iterative cycles of literature review, product study and analysis, as shown in Figure 21. In each cycle, the model has been adjusted after the analyses were completed in Product A. After the model was finalized, an evaluation study was performed using a different product, Product B. 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 C: The descriptive part of the study presented in paper C 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 activity, when the 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 C 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 B, is proposed and its usefulness in overcoming some of the barriers is discussed.

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 in which the multidisciplinary design context for aerospace products in addition to critical review of DFA and DFM methods with respect to welding are both presented; third, to develop a design method 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, as shown in Figure 21. In the final part of Paper D, an evaluation study of the method involving Product B 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.

3.2.1 Data collection methods employed

The Mixed Method Research approach consists of combining data collection methods 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 a description of how these methods have been generally applied in this research.

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.

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. However, 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 B (see Figure 24).

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 C. 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.

Diary notes: Throughout the entire research project, the researcher has made use of diary notebooks. A total collection of 23 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.

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

Inspection data: Another source of quantitative data has been production 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.

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 in relevant parts. 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 B (Figure 24) has served the author as a taxonomy or structure with which to code and analyze later interviews.

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), (Buur, 1990).

Reliability, as the concept for research verification, relates to the reproducibility of a result, demonstrating that the operations of a study, such as the data collection procedures, 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 mixed method research.

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 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 corresponds to external validity.

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, member checking, explanation building, peer reviews, clarification of the bias, intensive long-term involvement and rich data, to name a few. The tactics pertinent to this research will be discussed in greater detail at the end of the Results (see Chapter 5).

4 Results

This chapter presents the highlights from each appended paper, as well as a summary of the key contributions from each paper in relation to the research questions that they have attempted to answer. But first, to give an overview and better understanding of the connection between the papers, a short summary of each paper is given together with a figure that illustrates such a connection (see Figure 22).

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 gaps with regard to their industrial application and formulating opportunities for future research.

The starting point of **Paper B** is the producibility framework established in Paper A, within which quality and cost are considered to be the effects of producibility. On this basis and considering quality alone, Paper B presents a conceptual model that represents product quality creation during the manufacturing process of fabricated aerospace components. 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, a 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 factors that affect product quality during the manufacturing process. Factors derive from both the product and manufacturing systems.

The representation provided by the conceptual model will work as a foundation for the activities that are studied in the coming papers. Those activities include*: 1) Identify* what affects producibility*, 2) Measure* what affects producibility*, 3) Assess* the interaction between the factors that affect producibility *and 4) Predict* producibility.

Paper C touches upon Activity 2) Measure

First, **Paper C** highlights the need of reusing manufacturing data and information to feed probabilistic-based design activities that aim to predict the product quality with respect to the manufacturing process. Barriers to the reuse of inspection data into design activities are identified and discussed. In order to generate adequate process capability data that can be used in coming design activities, the conceptual model shown in Paper B is presented as a support of the inspection planning activity and as a way of overcoming some of the barriers identified.

Paper D touches upon the three activities 1) Identify, 3) Assess and 4)Predict

Paper D begins by providing a literature review of the DFM and DFA methods in order to justify why the design rules provided by these methods are not suitable for the case of welded aero structures. Thereafter, Paper D prescribes a method for generating new Design for Welding rules. The proposed Welding Capability Assessment Method (WCAM) is a tool with which to support the systematic identification and assessment 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 (labelled q_{DESIGN} in the conceptual model). In a following step, quantitative methods are proposed to assess the bandwidths to fulfill manufacturing quality and calculate tolerances on those design parameters in order to reduce the likelihood of welding failures, thus ensuring quality. Quality is one of the metrics of producibility as defined in Paper A. The bandwidths or allowed values of the design parameters constitute the design space within which any design variant produced will have the required manufacturing quality, i.e. the manufacturing capability space as described by the author. Having drawn the manufacturing capability space, prediction about producibility can be conducted in future design processes.

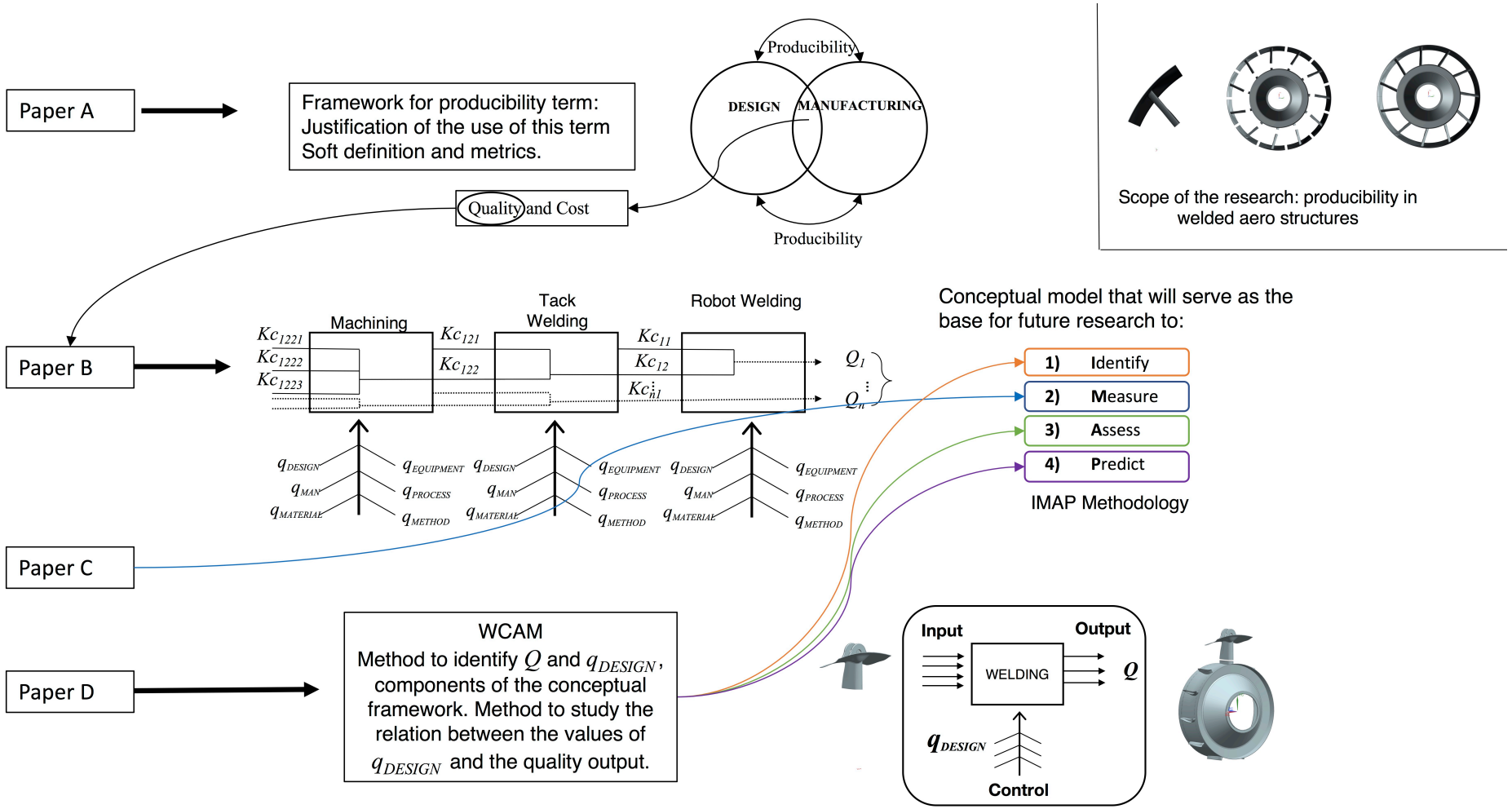

Figure 22 Illustrative connection between contributions to all Papers

4.1 PAPER A: An approach for producibility and DFM-methodology in aerospace engine component development

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 23 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 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 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.

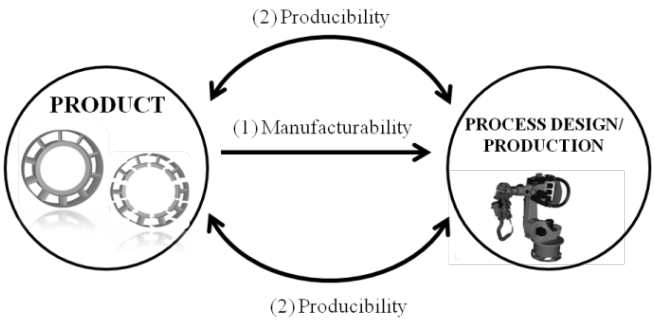

Figure 23 Producibility vs Manufacturability

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 expected process output in comparison to the requirements for each process step.
- Time – (total) process time. The total of time needed for each process step to fulfill all specifications and quality requirements (not logistics/material handling). There is an option to here exclude machine/automatic process time and include it in "Cost" only.
- Cost – (total) process cost. Refers to the total of manufacturing cost necessary for each process step, 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.

In the second part of the study presented in Paper A, a literature review was made of 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 chosen were: Integrated product development (IPD), Concurrent Engineering (CE), Systems Engineering (SE) and Set Based Concurrent Engineering (SBCE). The methods-tools chosen included: 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 and Design of Experiments (DoE).

First, an analysis was made of the potential of each of these methodologies and tools for considering producibility aspects in each of the product development phases. Second, some methodologies and tools were further analyzed with the objective of finding drawbacks and gaps in industrial application. From the gap analysis, opportunities for further research and development were suggested. This information is recorded in Table 2.

Table 2 Gaps and opportunity analyses from methodologies and tools reviewed within Design Engineering

Methods	Purpose	Gaps from lessons learned	Opportunities
IPD	Manage the sequence of activities. Deliver required information for project decisions	Not followed as defined Not enough cross functional work / too late	Follow the defined process /Improve communication Make the right competencies available Define standards for all producibility activities
CE	Enable multi-dicipinary work	Few methods to support cross functional work	Develop better methods (e.g. as the tools below)
SE	Manage stakeholder interests/requirements and plan to verify them	Not established yet All stakeholders are not defined Producibility is not measurable in early phases.	Introduce SE training & experience Identify producibility as a stakeholder Requirements and targets sholud be better defined and visualized /communicated
SBCE	Systematically build knowledge and step-by-step elimination of alternatives	Not established yet Lack of experience/ knowledge (new technologies)	Build up knowledge areas and apply them in methods for concept selection and other analysis tools Analyze producibility besides other requirements
DFM guides	Generic knowledge – rules/ recommendations about what is a better design – qualitative	Difficult to apply without experience Lack of guidelines for new technologies No quantitative data to compare alternatives	Need to continue building knowledge and defining applicable guidelines Documentation, visualization and communication
DFM/ DFA	Methods to analyse a certain aspect of the design – quantitative measures	Lack of experience and methods/data (new technologies) Tools exist, but are under development	Build more knowledge about cost, quality/capability and time for relevant materials and fabrication methods Investigate alternatives/solutions for IT support
Pugh	A matrix method to compare alternative solutions relative to each others	Overlapping and undefined criteria Concept ranking is subjective/ sensitive to knowledge level	Requirements / Concept selection criterias definitions Adapt ranking and scoring to the current knowledge level – use a maturity index / criteria

Highlights of the results shown in Table 2 can be summarized as follows:

In theory, the use of SE and SBCE is convenient to set and verify requirements, as well as building knowledge and facts about the different product concepts. However, producibility as a criterion and manufacturing as a stakeholder are still not fully considered. The implementations of these methodologies can be hampered due to: 1) the lack of producibility criteria to use in design evaluations; 2) the subjective nature of existing information based on expert opinions; 3) the lack of capability knowledge and data regarding new technologies (new welding methods and advance materials); 4) the lack of guidelines for new technologies; 5) the lack of quantitative data; 6) the lack of quantitative approach methods.

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

- The need to clearly understand what contributes to producibility and how to measure it.
- The need to develop additional tools to help measure and evaluate producibility.
- The need to implement a methodology during the product realization process that would integrate all methods and tools needed to evaluate producibility.

Main scientific contribution: A framework for producibility, including a definition, metrics and a collection of Engineering Design methodologies and tools. In addition, research gaps and needs have been identified within the field of Engineering Design.

Main industrial contribution: An analysis of the industrial use and potentiality of a number of methodologies and tools for considering producibility. A framework that works as a foundation with which to evaluate producibility with metrics/criteria.

The results from Paper A address the producibility phenomenon from the design field, thus contributing to answer RQ1.

4.2 PAPER B: Development of a conceptual framework to assess producibility for fabricated aerospace components

Whereas Paper A looks at how producibility can be considered during the design process, Paper B 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 B 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 24).

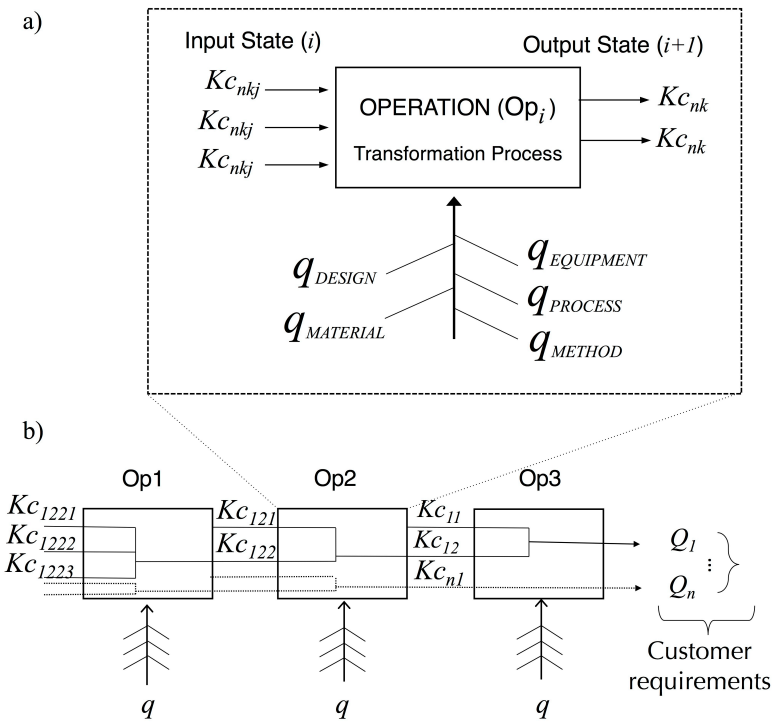

Figure 24 Producibility model: conceptual framework to represent product quality creation during the fabrication process

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. From this definition, 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 24 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) into a desired output state (Od_2). In the same way, the model presented in Paper B (Figure 24 a)) describes the transformation of key characteristics (KCs), i.e., the product characteristics with variation critical to the function and performance quality of the product (Thornton, 2004). In addition, the transformation that occurs 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 control parameters acting as sources of variation, an Ishikawa diagram developed by Söderberg et al. (2006b) was adopted in the model. The denotation of control factors is inspired by the *q-quality* concept developed by Mørup (1993). The 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 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.

Figure 24 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 (Q_i). The *Q-quality* concept was adopted from (Mørup, 1993). The sequence of KCs is made so that inputs and outputs of each operation (Op_i) can represent variation propagation. In a similar fashion, some authors such as Dantan et al. (2008), Mirdamadi et al. (2012) and Mathieu and Marguet (2001) have used the KC flowdown approach developed by Thornton (2004) to determine the drivers of quality. What is unique in this proposed model is that the product system decomposition represented by the KC flowdown, intended for assembled products, is aligned to the assembly process composed of a number of operations as represented in Figure 24 b). By doing so, functional requirements (carriers of quality) can be determined to be top-level KCs and broken down into KCs at each product subsystem, thus at each assembly operation. This decomposition allows a pull approach (Ericson Öberg, 2016) because information is pulled from the top level of product down to assembly operations.

The various sources of variation (denoted as q_{DESIGN}, q_{METHOD}, $q_{MATERIAL}$, $q_{EQUIPMENT}$, $q_{PROCESS}$ in Figure 24 a) contribute to the variation induced during the transformation of KCs along the sequence of manufacturing operations. An example is given in Figure 25 to illustrate the use of the model.

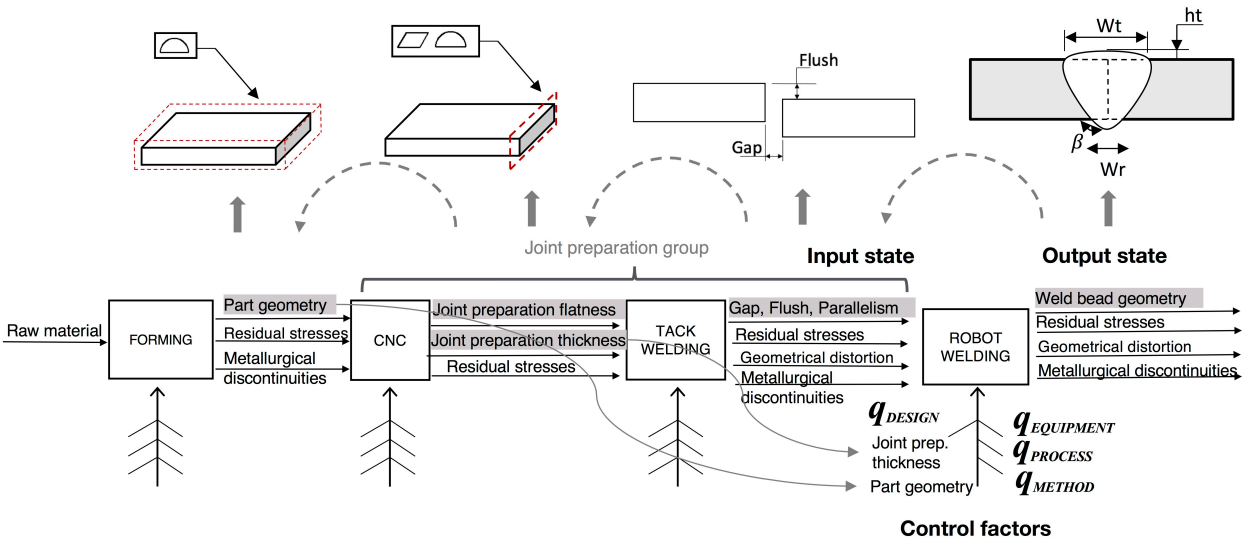

Figure 25 Illustrative example of producibility model used for industrial application

In this example, the quality of two parts that intend to be welded for an aerospace application is analyzed. In particular, the quality of the weld bead is in focus. The geometry of the weld bead is described by certain parameters or KCs (*Wt, Wr, β, ht*) that define weld bead quality. These KCs have certain tolerances to be able to fulfill life and aerodynamic requirements. Dimensional variation outside these tolerance limits will not be acceptable with regard to performance quality. 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. So 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 (Computer Numerical Control CNC), the KC flatness of the surfaces to be welded and the KC weld interface profile need to be assured to deliver proper weld alignment conditions while tacking. Ultimately, the KCs defining the part shape quality given by the net shape forming process will affect flatness and thickness quality.

Furthermore, some KCs created during previous operations (such as part geometry and joint preparation thickness, as indicated in the example of Figure 25) although being design parameters can act as control factors (q_{DESIGN}) to the robot welding operation system. For example, part thickness (q_{DESIGN}) in combination with the type and equipment of welding method (q_{METHOD} and $q_{EQUIPMENT}$) will determine the amount of heat needed to weld, which eventually will influence weld beady geometry.

At this stage, this systems-based representation helps to classify, structure and visualize all factors affecting product quality during the manufacturing process, working as a taxonomy. Each operation becomes a delimited system in which outputs, inputs and control factors are represented. Thus, the representation provided by the *producibility* conceptual model helps to understand how manufacturing variation originates and propagates, working as a basis for activities studied in coming papers. These activities include*: 1) Identify* what affects producibility*, 2) Measure* what affects producibility, *3) Assess* the interaction between factors that affect producibility and *4) Predict* producibility.

Main scientific contribution: A conceptual framework with which to describe the phenomenon under study, i.e. the product quality creation during the manufacturing process.

Main industrial contribution: A model for producibility working as a taxonomy for welded aerospace structures.

Paper B studies the producibility phenomenon from the manufacturing aspect, thus contributing to answer RQ2.

4.3 PAPER C: Enabling reuse of inspection data to support robust design: a case study in the aerospace industry

One of the gaps, identified in Paper A, when applying methodologies and methods to ensure producibility 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 C considers this matter further. First, Paper C highlights 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. Much of these approaches assume the existence of process capability data. However, inspection data are mostly employed to optimize production. Thus, the two research questions that guide this paper are:

Paper C RQ1: What are the barriers to reusing inspection data during robust design activities?
–That is: If we measure during inspection activities, why are not we reusing that data?

Paper C RQ2: How can inspection planning and execution be supported so that they generate adequate process capability data to be reused?
–That is: What can we do to measure the right things in order to utilize these data during probabilistic-based design activities?

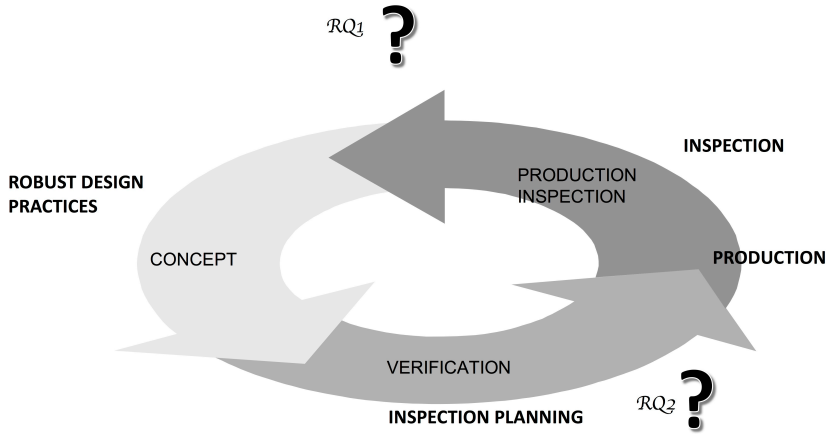

Figure 26 Case study research questions allocated within the geometry assurance cycle.

To answer RQ1, a classification of barriers to reuse inspection data into design activities is presented. 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 3).

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?*

[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.

Table 3 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

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.

After presenting this classification, Paper C elaborates further on information barriers. The reasons why the inspection and measurement processes do not generate adequate data content are first because the reasons for measurement have not been clearly defined (*Why* to measure). The activities to assure quality have not been identified. Without an established quality assurance cycle, the new stakeholders of the data have not been contemplated. Still, production optimization and repair activities are the predominant stakeholders. Second, *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 parameter causing variation in those key product characteristics have not been properly identified as measurement features. In addition, *How* to measure needs also to be planned, identifying the metrics with 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 or to perform root cause analysis during production.

With a focus of overcoming the information barriers, RQ2 was formulated. The conceptual model presented in Paper B is then proposed to be the core structure with which to support the inspection planning activity in order to clarify *Why*, *What*, *How* and *When* to measure. First, there is a need to implement a Quality Assurance cycle to identify new users of inspection data and pull the required information. Then, the proposed model (Figure 24) would connect user needs with measuring data. In the model, top-level product requirements directly linked

to product functionality (Q_i) are systematically broken down to key product characteristics (KCs) at each assembly level and, consequently, at each manufacturing operation. Linking the transformations of KCs operation by operation to product functionality would tell *What* to measure: which product characteristics (KC) to measure before (KC_{nkj} at input state) and after the operation (KC_{nk} at output state), as well as which manufacturing parameters and factors (q) need to be measured to control the output KCs from each operation. Therefore, the model proposed helps 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.

Main scientific contribution: A generic list of barriers to reuse inspection data in robust design activities. Paper C builds upon the conceptual model presented in Paper B regarding Activity 2) *to measure.*

Main industrial contribution: An identified list of problems in reusing inspection data in design analysis. In addition, a core support with which to structure the inspection activity and thus the measure activity to produce the right data content.

Paper C contributes to the descriptive phase of the design phenomenon and thus RQ1 since it identifies the needs for and barriers to reusing data and information from manufacturing during design. This paper also contributes to the prescriptive phase and RQ3 since it shows how the *producibility* conceptual model (created in Paper B) can serve as a tool to plan the measurement activity in order to generate adequate data for reuse. The ultimate goal of gathering process capability data is to create predictive producibility models.

4.4 PAPER D: A Welding Capability Assessment Method (WCAM) to support multidisciplinary design of aircraft structures

The *producibility* conceptual model developed in Paper B has been presented as 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, when and by what metrics. The model aims to classify and represent the different factors affecting the product quality creation during the sequence of manufacturing operations. However, how to extract and assess those factors is not addressed by the model. Thus, in Paper D a method named the Welding Capability Assessment Method (WCAM) is presented. This method supports the systematic identification and assessment of factors related to design structure and geometry, which affect the product quality resulting from the fabrication process, specifically the welding operation. The aim is to identify input and output variables in the welding operation system and evaluate the relation between these variables. In this way, the welding capability space can be analyzed, thus supporting design space exploration.

The Welding Capability Assessment Method (WCAM) entails two mains steps, outlined in Figure 27:

***Step 1*:** The first step involves identifying the key product characteristics (KCs), input and output of the welding operation, that are critical to ensure product performance quality (*big Q-quality).* The target value and tolerance of each output KC are then set to fulfill technical requirements, derived from customer demands.

***Step 2*:** The second step involves identifying and assessing the control factors (*small q-quality*) that influence the welding operation output, which has been identified in Step 1, however only those factors related to product structure and geometry (q_{DESIGN}). This step consists of three substeps:

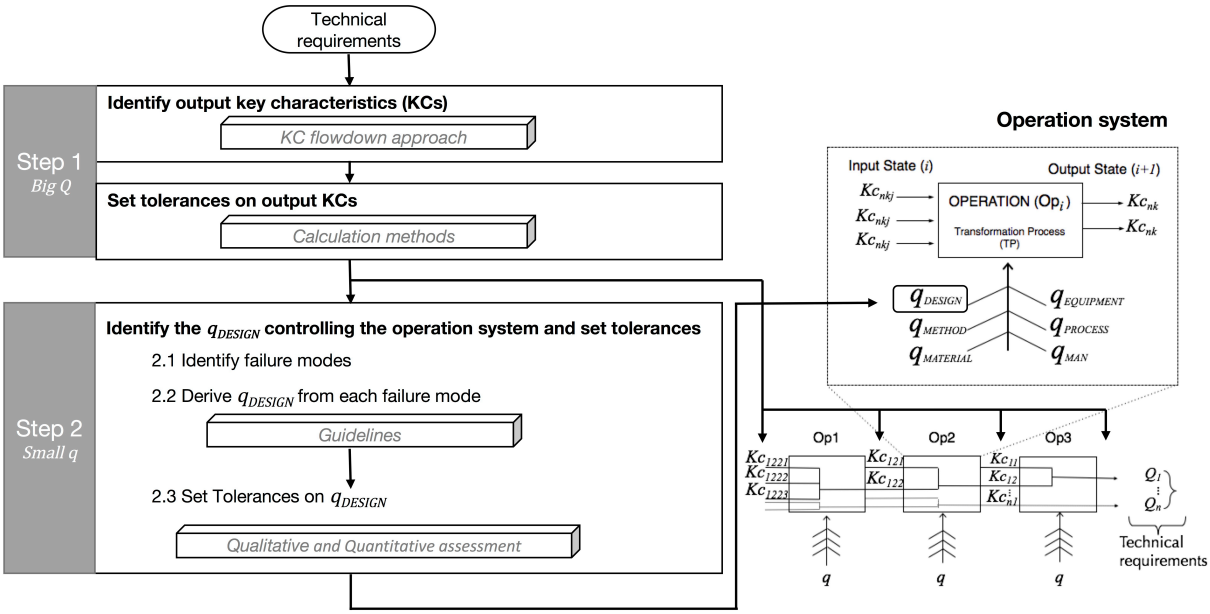

Figure 27 WCAM method: steps and tools

Step 2.1: the failure modes during welding are identified.
Step 2.2: the design parameters, q_{DESIGN}, leading to those failure modes are derived.
Step 2.3: ways to assess the potential value of these design parameters are proposed to avoid welding failure, thus ensuring product quality. This step involves setting tolerances on design parameters that act as control variables on which welding output is dependent. In this way, limits on the welding capability space can be established.

Different tools are employed in each of the steps within the WCAM-method. In Step 1, the KC-flowdown from Variation Risk Management (Thornton, 2004) together with calculation methods (see Table 4) are used to break down product-level technical requirements into requirements at each subsystem level, thus requirements at each assembly level. In this way, Key Characteristics (KCs) can be identified as outputs of each operation. In Figure 25, an example of a KC-flowdown has been illustrated. In addition, Table 4 presents an array of tools to set the tolerance limits on the output KCs in order to ensure adequate performance of welded aircraft structures.

In Step 2, the objective is to identify and assess the product design parameters (q_{DESIGN}) that cause manufacturing variation on the output KCs of the welding system, identified in Step 1. The ultimate objective is to find relationships (sensitivity coefficients) between control variables (q_{DESIGN}) and output variables (KCs). In this way, the capability space can be drawn and such information utilized in new projects to predict product quality with respect to welding processes. Table 5 presents the three sub-steps of Step 2.

Table 4 Calculation methods to set tolerance limits in output KCs

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	Fatigue life	Structural finite element analysis	KC4 + T
	Aerodynamics	Computational Fluid Dynamics (CFD)	KC5 + T
	Performance of the next assembly	Variation simulation	KC6 + T

Table 5 Step 2 in Welding Capability Assessment Method

Step 2.1	Step 2.2	Step 2.3			
Failure mode	q_{DESIGN}	**Qualitative assessment** *(Higher probability of failure if q_{DESIGN}...)*	**Quantitative assessment** Standards Handbook	Physical test	Simulation test
Incomplete joint penetration	*Thickness (t)*	Increases	Yes	Yes	No
Incomplete joint penetration Underfill & excessive reinforcement root side	*Thickness uniformity (u_t)*	Increases	No	Yes**	No
Overlap root side Limited accessibility to inspect	*Inner radius (r)*	Decreases	No	Yes**	CAD model offset Path planning simulation
Limited accessibility to weld (limited robot rotation) Incomplete joint penetration Overlap top side Distortion (Multiple weld passes)	*Outer radius (R)*	Decreases	No	Yes**	Path planning simulation Authors´ proposition * 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

* See Case Study Section.
** Expensive test if many product geometry variants need to be tested.

Table 5 works as a guideline with which to identify failure modes and connect them to specific design parameters (q_{DESIGN}). Furthermore, the objective is to support tolerance settings on the design parameters identified (q_{DESIGN}) in order to guarantee a successful operation. This is performed by combining qualitative and quantitative assessments. For each of the (q_{DESIGN}) extracted, Table 5 indicates a higher probability of failure if the nominal value of (q_{DESIGN}) increases or decreases. This qualitative assessment serves as a first-glance guide to evaluate the impact of design on welding outcomes. However, this estimate needs to be complemented by quantitative assessments to provide a more accurate evaluation supporting the tolerance setting process. Thus, on the right side of Table 5, methods for quantitative assessment are presented.

This method has been applied to an industrial case study 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 weld bead geometry for the particular case of GTAW-welding and super nickel alloy material. Five different thicknesses and five different radii combined 25 different variants forming the design space to be explored. The results of the welding simulation shown in the Figure 28 graph indicate that the quality of the weld bead (related to the failure mode overlap) can only be guaranteed for thickness 1.5 and radius 3.5 ± 3mm. Interviews with experts confirmed these results.

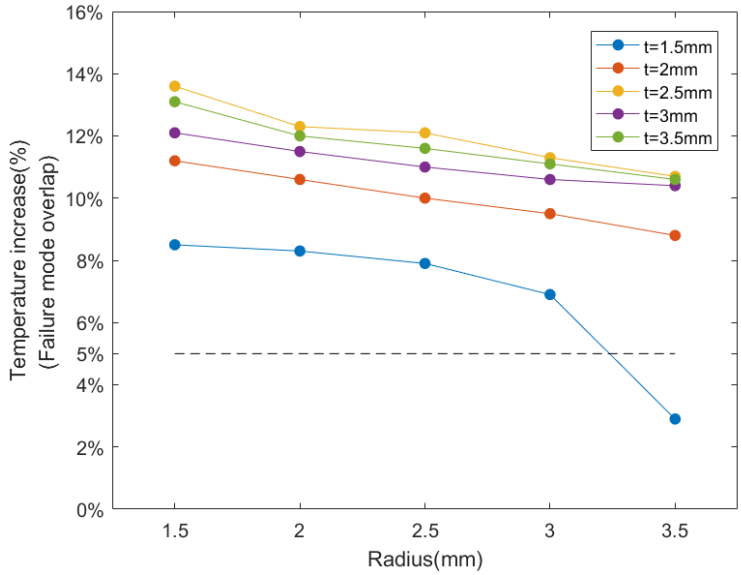

Figure 28 Graph representing relationship between the design parameters (radius and thickness) and temperature increase (failure mode overlap)

Figure 28 represents the capability space of a certain welding technology and material when the output studied involves weld bead geometry. The graph illustrates the relationship between the independent variables thickness and radius and the dependent variable overlap. The resulting manufacturing capability space can be reused in future projects.

Main scientific contribution: the WCAM method is an Engineering Design tool with which to evaluate geometry variants of welded products concerning producibility. Results from this paper builds upon the model introduced in Paper B in relation to Activity 1) *Identify* and Activity 3) *Assess*. With this method at hand, welding process capability data can be generated and utilized in future design development processes to predict producibility.

Main industrial contribution: the WCAM method to evaluate welding capabilities for a specific welding technology and material. This method represents a systematic way of bulding knowledge building on quantitative data as facts, reinforced by expert judgements.

Paper D provides first a literature review of DFM and DFA methods to justify why these existing methods are not suitable for the case of welded aero structures and points out the need for new methods, thus contributing to RQ1 and the study of producibility from the design phenomenon. Paper D also includes an exhaustive descriptive study of the welding operation and contributors to variation, thus answering RQ2. Finally, the WCAM method contributes to the prescriptive phase of this PhD project and RQ3.

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.

5.1 ANSWERING RESEARCH QUESTIONS

The four appended papers in this thesis contribute to answering the three research questions posed in the Introduction. As a guidance for the reader, Table 6 shows which paper that has contributed to which research question and its level of contribution.

Table 6 Connections between papers, study areas, DRM phases and research questions

Results	Study Area		Descriptive Study I		Prescriptive Study
Papers	Design	Manufacturing	RQ1	RQ2	RQ3
A	√		✈	✈	
B		√		✈	
C	√	√	✈		✈
D	√	√	✈	✈	✈

✈ strong contribution; ✈ low contribution

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

This question is first addressed in Paper A, in which a review of methodologies, methods and tools available in literature to consider production aspects during the design process is presented. In addition, a study at the industrial partner is carried out to analyze how these methodologies, methods and tools are being applied to identify the difficulties and barriers encountered in their industrial implementation.

From this analysis, it can be concluded that in theory, the use of methodologies, such as Systems Engineering and Set-Based Concurrent Engineering, is convenient to set up and verify requirements, as well as building knowledge and facts about the different product concepts. However, producibility as a criterion and manufacturing as a stakeholder are still

not fully considered. DFM and DFA methods are to some extent useful. However, for the case of welded aerospace structures, these methods present some barriers and limitations.

The first barrier encountered is connected to the type of application and optimization focus. Paper D gives a more exhaustive analysis, concluding that DFA and DFM focus on optimizing time and cost rather than quality in forming and assembly processes. Welding is vaguely treated and common applications of these methods are complex products in the number of parts for which geometrical and structural modifications do not substantially affect product performance and functionality. However, the products and applications that build the context of this thesis, welded aerospace structures, are integrated solutions, in which geometry is highly linked to performance (geometry influence function). At the same time, the fabrication solution influences geometry and geometry in turn influences the fabrication solution. 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 these products. Therefore, for this type of application, producibility criteria cannot solely rely on optimizing time and cost spent on manufacture and assembly but rather on the quality built into the product.

Now, having defined the product and optimization focus that stems from the context of this research, further conclusions can be presented. From the analysis performed in Papers A and D, a number of barriers have been identified that can hinder the implementation of some of the reviewed methodologies and tools for making producibility assessments of fabricated structures during design phases. These barriers are: 1) the lack of detailed producibility criteria for use in design evaluations; 2) the subjective nature of existing information based on expert opinions; 3) the lack of capability knowledge and data on new technologies (new welding methods and advance materials); 4) the lack of guidelines for new technologies; 5) the lack of quantitative data; 6) the lack of quantitative methods.

Therefore, the underlying problem of implementing methodologies and methods with which to ensure producibility analysis for welded integrated structures is attributable to the lack of detailed criteria with which to measure and evaluate producibility and in addition, the lack of corresponding quantitative data to carry out those evaluations.

Manufacturing and inspection data are currently being produced to monitor, control and optimize production. 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 to virtually ensure product quality and to make products more robust against manufacturing variation. But, why are inspection data and process capability data not reused in design activities today? Paper C gives an answer by identifying and classifying specific barriers to the reuse of capability data during robust design activities. These barriers are classified into information, technical and organizational barriers. Information barriers relate to the quality of data content. Technical barriers are connected to the quality of inspection, measurement and data management systems. Organizational barriers relate to the collaborative interaction between design and manufacturing. Still, these three types of barriers are interconnected. For example, the quality of the measuring system implicitly affects the quality of the data.

This thesis and Paper C in particular focus on analyzing information barriers. The information aggregated from the 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 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 question.

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

Producibility is the preferred term over manufacturability for the case of welded aerospace applications. This argumentation can be found in Paper A. Basically, manufacturability and DFM have been traditionally used in applications where welding processes have been vaguely considered and in products in which geometry is not highly linked to functionality and performance. With manufacturability, 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 characteristics. However, 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. As explained in the introduction, producibility is an emerging property from the interaction of two technical systems, the product/design and the manufacturing system. Without a design at hand, we cannot talk about its producibility and the same occurs without a manufacturing solution.

Producibility property already emerges from the early phases in the design process where design structure and 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 as argued in Paper A. The quality concept is taken from Quality Engineering Theory and is closely related to process capability. Thus, quality is achieved if the output variation of the manufacturing operation ($\pm 3\sigma$) is within tolerance limits (TL).

$$\text{Process capability: } C_p = \frac{TL}{\pm 3\sigma}$$

The cost concept does not only cover material, production and production time cost. It also covers the cost of quality failure. In aerospace applications, scrap rates are extremely low if existence. Thus, quality failures during production are fixed with rework or sometimes even redesign loops. It is the cost of quality failures what prevails over manufacturing cost.

Consequently, in aerospace applications, the focus is shifted towards quality and how quality is being built into the product during its manufacture. Therefore, in order to operationalize producibility and be able to measure and then evaluate it, there is a need to model the manufacturing process to show how variation is created and propagated operation by operation.

As represented in Figure 29, quality is designed into an assembled product by specifying basic characteristics (KCs), such as structure, form, dimensions, surface characteristics and material. Through those characteristics, the design (the product) carries customer quality (big *Q-quality concept*). The manufacturing process in turn builds that quality into the product. Operation by operation, each key product characteristic (KC) is transformed until final quality is delivered. In addition, the transformation that occurs at each manufacturing operation is controlled by a number of parameters (small *q-quality concept*).

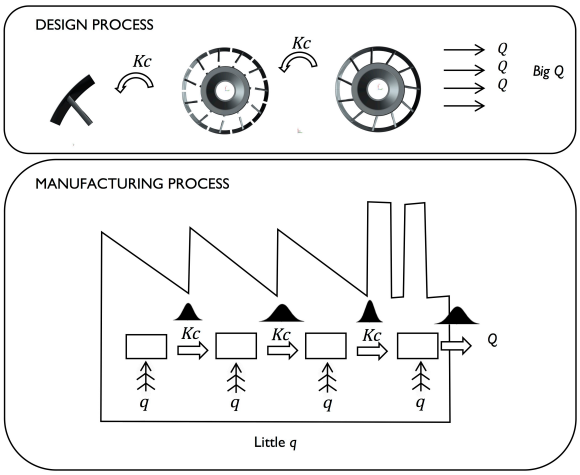

Figure 29 Phenomenon representation: Product quality creation

In Paper B, a conceptual model is proposed to describe product quality creation during a manufacturing process. See Figure 30. The model represents the key product characteristics (KCs) created and transformed operation by operation, which carry product quality (*Q*). In addition, the model represents the factors (*q*) that affect that transformation contributing to variation on these KCs, thus impairing product quality. The output KCs of each operation with their target values and tolerances represent the product quality (*Q-quality*), whereas the Ishikawa diagrams at each manufacturing operation represent the contributors to manufacturing variation from both product-design and manufacturing systems, thus representing internal *q-quality*. In this way, manufacturing variation can be compared to tolerance limits in order to evaluate quality. Moreover, sources of variation can be controlled to minimize output variation.

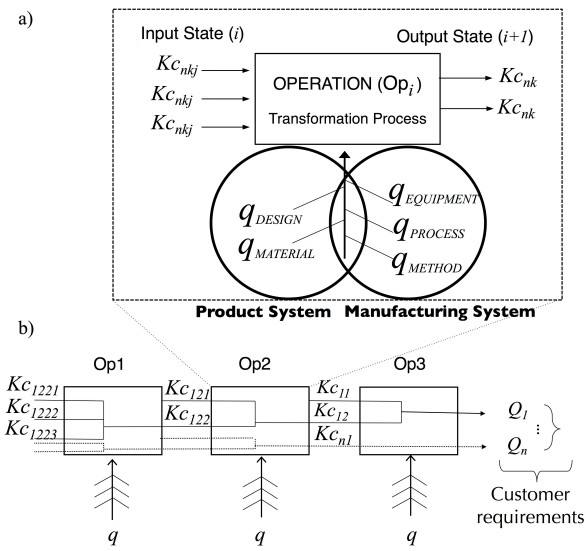

Figure 30 Producibility model as presented in Paper B with circles representing Figure 31.

In the conceptual model presented in Paper B (Figure 30), 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 31.

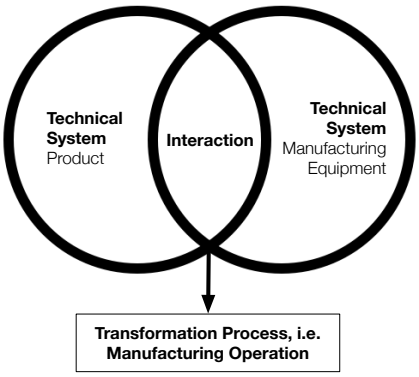

Figure 31 The interaction of two technical systems (Product and Manufacturing) affects the transformation process that occurs during a manufacturing operation

Although being a combination of existing models in literature, what makes the proposed conceptual model (Figure 30) unique is that it can represent how technical requirements are broken down into requirements at product subsystems and how this is aligned to the fabrication process. In this way, requirements on each operation output are specified, connecting operation outputs to product performance quality. This model represents a pull approach or way of working (Ericson Öberg, 2016) and as a consequence, each manufacturing operation is specified to deliver product quality.

To conclude, the representation provided by the conceptual model (Figure 30) will work as a basis for a methodology that will include the following activities:*1) **I**dentify what affects producibility, 2) **M**easure what affects producibility 3) **A**ssess the interconnection between factors that affect producibility and 4) **P**redict producibility.* This might be named the ***IMAP*** methodology. A discussion of this potential methodology will be given in the answer to RQ3.

Furthermore, Paper D uses the producibility model presented in Paper B as a basis for building a method to assess the capability of the welding operation, the WCAM method. Within Paper D, an exhaustive study of the welding operation system is carried out to identify factors contributing to variation and thus to producibility. Only contributors that relate to product design are considered (q_{DESIGN}). Depending on the value given to these design parameters (q_{DESIGN}), the welding quality output will vary. The ultimate objective is to find the design parameters that act as independent variables within the system and find the relationship and sensitivity coefficients with the dependent variable, represented by the welding output. In this way, capability information can be built and utilized to make producibility assessments during design. This argument will be further addressed below.

RQ3: How can producibility assessments be supported during multidisciplinary design of fabricated aerospace components?

From the answer to RQ1, it can be concluded that if producibility assessments cannot be currently performed, this deficiency is attributed to the lack of producibility criteria and capability data, among other barriers. As today, advancements in computer technology and software allow the generation and analysis of a large number of design variants from the perspective of mechanical engineering and aerodynamics disciplines. However, the assessment of manufacturing capabilities based on CAD geometry is, if possible, mostly limited to interactive and manual analysis of a single design. In industry, in the particular case of welding, process capabilities are physically tested for those phenomena that 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 to finding the process parameter window. This situation translates into a lack of manufacturing capability data and quantitative data with which to perform optimization and evaluate trade-off alternatives in terms of producibility during design space exploration and analysis, as discussed in Papers C and D.

One of the root causes to this problem is the complexity of the welding system and the many factors that affect the quality of welding output. During welding, heat transfer, melting, solidification, microstructure transformation, macrostructure discontinuities, shrinkage and distortion are the many phenomena that occur. In industry practice, welding simulations (sometimes combined with variation simulations) are extensively employed to calculate distortion and residual stresses. However, not all phenomena related to welding can be virtually modelled. Understanding causes and effects still relies on expert judgements. The quantification of sensitivity coefficients within the welding system relies to a great extend on physical experimentation, efforts that become costly when many geometrical variants need to be tested. This deficiency indicates a need for virtual assessment methods and for planning systematic experimentation to produce data that can be reused in future projects. Therefore, to ensure quality earlier during the design process and to search within the design space for solutions with acceptable welding capability levels, expert knowledge must be structured and automated. Patterns and engineering rules need to be extracted from specialized information about welding problems, know-how, inspection and simulation data.

As argued in Paper C, a structured approach to clarify *why*, *what*, *when* and *how* to measure would enable the creation of adequate manufacturing data that carry pertinent content and information to be utilized for probabilistic activities during Robust Design. The conceptual model presented in Paper B, see Figure 24, serves this purpose since it works as a taxonomy to structure and classify what and when key product characteristic (KC) carriers of quality are created during the manufacturing process and how variation in these KCs is propagated along the assembly process. In addition, factors contributing to that variation (q) are classified according to whether they belong to design or manufacturing systems. This structure allows us to isolate manufacturing operations for their analysis by identifying input (X) and output (Y) variables in the system for the future objective of building "rules". However, the model by itself does not prescribe how to identify, assess and evaluate the relationship between variables and sensitivity coefficients.

Paper D goes a step further into solving the problem and proposing a method, the Welding Capability Assessment Method (WCAM), with which to assess the welding capabilities and generate pertinent data to draw the manufacturing capability space. That is the design parameter space that fulfills manufacturing quality, as defined in Paper D. The manufacturing capability space represents the range of values that design parameters under consideration can adopt while still delivering manufacturing variation within tolerance limits.

The core of the WCAM method is formed by a flowchart of steps connected to an array of tools (see Figure 27). In the first step, a KC flowdown aligned to the assembly process is used to break down product technical requirements into Key Characteristics (KCs) at each product subsystem level. Calculation methods are then applied to calculate tolerances on the KCs identified to ensure performance quality (see Table 4). In this way, input and output KCs of each operation within the producibility conceptual model can be identified. Aligning a KC flowdown to the assembly process allows working in a pull approach since the top product level requirements connected to customer demands are broken down backwards into requirements at each assembly operation (see example in Figure 25). 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, guidelines created by the author and presented in

Table 5 are used to first identify potential failure modes within the welding system and second to connect them to design parameters (q_{DESIGN}) that act as causes. 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 assess relationships between both variables and evaluate sensitivity coefficients to build engineering rules.

Paper D also demonstrates the strength of combining qualitative and quantitative assessments when evaluating welding capabilities. Due to the stated lack of virtual tools for assessment, expert knowledge still plays an important role within these evaluations. In the Case Study presented in Paper D, the welding simulation results are verified by expert judgements.

All in all, the proposed *producibility* conceptual model and *WCAM* method establish the structure and basis with which to generate adequate manufacturing data and extract interactive engineering rules, which will lead to increased virtual development in the future. WCAM represents an advancement from traditional qualitative guidelines and expert judgements about welding difficulties towards a more quantitative approach. This method also represents a new way to perform DFM analysis with a manufacturing quality focus, replacing traditional DFM tools that focus purely on time or cost.

In multidisciplinary design, produciblity assessments are better supported when working with a Set-Based Concurrent Engineering (SBCE) approach. In SBCE, as explained in the Introduction and Frame of Reference, a set of design solutions are generated and kept open until enough information has been acquired to eliminate a variant, where applicable. To evaluate the feasibility of the different variants and to explore the design space from a producibility perspective, capability data and engineering rules relating design parameters to welding output are needed. Data and information about the impact of the design on the fabrication process, i.e. capability data, can be used during the design process to obtain a more robust solution. Capability data can be used in simulations and in probabilistic design to draw ranges of action from a producibility perspective in multidisciplinary design, i.e. drawing the manufacturing capability space, as defined in this thesis. The WCAM method proposed attempts to generate such a data and capability space in a planned and structured way.

Once data and information have been generated by WCAM, they can be adapted and incorporated into a multidisciplinary design analysis and optimization (MDAO) environment, in which trade-offs will be made with other disciplines, including mechanical engineering and aerodynamics. This aspect will be considered under Future Research Agenda.

To conclude, the representation provided by the *producibility* conceptual model (Figure 24) together with the proposed WCAM method work to support a methodology that includes the following activities:

1) ***I**dentify* what affects producibility
2) ***M**easure* what affects producibility
3) ***A**ssess* the interaction between factors that affect producibility
4) ***P**redict* producibility

The above could be named as the ***IMAP*** methodology. The author´s intention is not to replace current methodologies that can be found in literature, such as DMAIC (from Six Sigma) or IAM (from Variation Risk Management); see Frame of Reference Chapter. IMAP shares similar phases and purpose. However, the real contribution of this thesis to academia and industry is the model and methods presented in IMAP which are specially tailored to the case of welded structures. The WCAM method and tools contribute to expanding the Geometry Assurance toolbox to a Quality Assurance cycle specifically tailored for welded aerospace structures. A more detailed discussion on the impact of the thesis results is presented in the coming subsection.

5.2 THESIS RESULTS IMPACT

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 tp industry must be guaranteed to avoid ending up in a "valley-of-death" situation between academia and industry, as described by Flyvbjerg (2006). Therefore, to clarify and illustrate the line of argumentation that shows the industrial relevance of the research results presented in this thesis, an Impact Model (Blessing and Chakrabarti, 2009) has been created (see Figure 32).

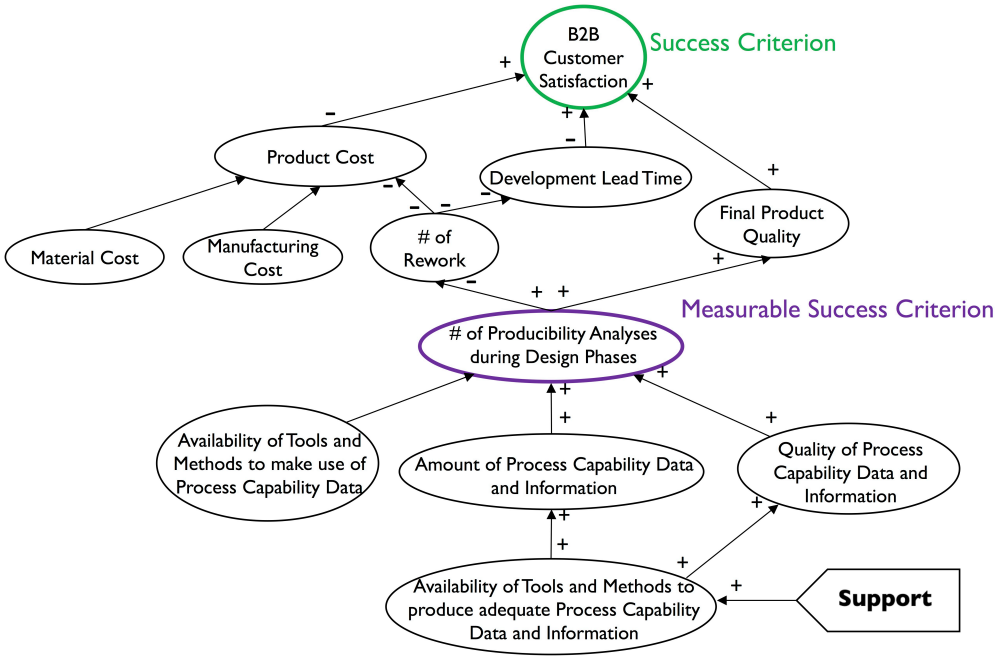

Figure 32 Impact model used to discuss impact and validity of the thesis results (applied from (Blessing and Chakrabarti, 2009)

The impact model (Figure 32) illustrates a network of consequences where the key factors identified act simultaneously as causes and effects, either positively or negatively. This cause-and-effect chain represents the line of argumentation for developing specific support. In the impact model presented, the ultimate goal to which research results intend to contribute is the customer satisfaction, represented by the success criterion. The support, represented by research results, is directly connected to the key factor: *"Availability of Tools and Methods to produce adequate Process Capability Data and Information"*. The actual support presented in this thesis is the producibility model and WCAM method that in a structured and systematic way intend to produce adequate process capability data to be utilized during producibility assessments. This support will first increase the amount and quality of process capability data and information. Following the chain of causes and effects, the support will then increase the number of producibility analyses during design phases, which in turn will reduce the amount of rework and consequently product cost, development lead time and increase final product quality, which will ultimately impact positively on customer satisfaction. A Measurable Success Criterion must be identified due to the impossibility of evaluating the Success Criterion within the timeframe of the research project. The Measurable Criterion has been defined by "*# of producibility Analyses during Design Phases*" and it will be further discussed

in Section 5.3.

Although academic and industrial contributions to each single paper have been described in the Results Chapter, both contributions are here discussed in more general terms:

– *Industrial Contribution*: the impact model described above represents the industrial contribution to the research outcome, i.e. support during the product realization process to create process capability data and information that can be utilized to make producibility assessments during design space exploration and analysis.

– *Academic Contribution*: this 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 conceptual model and a method (the WCAM) 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 EVALUATING THE QUALITY OF THE RESEARCH RESULTS

As explained in Section 3.4., 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 four papers 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 specifics whenever appropriated.

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 23 notebooks. 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 21 meetings were conducted and 21 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. When analyzing interviews, triangulation techniques could be applied due to the intermittent collaboration of Master thesis students within the development of this research project. When working with Master thesis students, interview notes were cross-checked and commented upon and audios listened to several times when required.

The model developed in Paper B has been verified by applying it to the fabrication process of two product variants 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 failure modes and connected design parameters (q_{DESIGN}). In the case study performed in Paper C, Six Sigma methods were used to collect and analyze the data. The DMAIC approach within Six Sigma ensure a systematic way of working.

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 five 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"*.

Triangulation of both data sources and analyses has been the vital to validate research results. As discussed in the Research Approach Chapter, 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.

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. 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 also used in Paper D to build validity with regard to the welding failures and potential causes identified.

The above methods engender 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, which constitutes a type of multiple-case study, in which the logic applied in the first has been replicated in the second case study.

The external validity can also be evaluated with the help of the impact model presented in Figure 32. The impact model, as explained above, represents the line of argument for developing specific support. If the research outcome is valid, the impact of such support into the industrial problem initially described will be positive, thus moving from the existing to the desired situation. The criterion to evaluate the success of the research outcome is defined by the Success Criterion, "*Customer Satisfaction*" (see Figure 32). However, due to the impossibility of evaluating the Success Criterion within the time frame of the research project, a Measurable Success Criterion *"# of producibility analyses during design phases*" has been identified. Therefore, this criterion will be utilized in the near future development of this thesis towards the Doctorate to evaluate the research outcome, thus completing the last phase of Design Research Methodology.

6 Conclusions

In this final chapter, results are summarized and conclusions are drawn, pointing also out the direction of future work.

The research presented in this thesis has focused on producibility problems for the particular case of welded structures in high performance applications. Academically, this research has aimed at contributing on understanding, as well as methods and tools to the field of Quality Engineering in general and Geometry Assurance and Variation Management in particular.

The first research question (*RQ1*) aimed at understanding why producibility assessments are currently poorly conducted during the design process of fabricated aerospace components. Methods and tools in the literature were analyzed to understand the industrial implementation difficulties encountered. In theory, the use of methodologies, such as Systems Engineering and Set-Based Concurrent Engineering, is convenient to set and verify requirements, as well as building knowledge and facts about the different product concepts. However, producibility as a criterion and manufacturing as a stakeholder have still not been fully considered. DFM and DFA methods are useful to some extent. However, for the case of welded aerospace structures, these methods present some limitations. In the literature reviewed, DFA and DFM focus on optimizing assembly and forming process time rather than product quality. Welding is vaguely treated. In addition, common applications of these methods are complex products in the number of parts for which geometrical and structural modifications do not substantially affect product performance, contrary to the type of products that have been the focus of this thesis, integrated and high performance structures.

Further conclusions are that implementation of some of the reviewed methodologies and tools can be hampered due to:

1) the lack of producibility criteria to use in design evaluations;
2) the subjective nature of existing information based on expert opinions;
3) the lack of capability knowledge and data regarding new technologies (new welding methods and advance materials);
4) the lack of guidelines for new technologies;
5) the lack of quantitative data;
6) the lack of quantitative approach methods.

Therefore, it can be concluded that the underlying problem of implementing methodologies and methods to ensure producibility analysis can above all be attributed to the lack of detailed criteria to measure and evaluate producibility and second, the lack of corresponding quantitative data to carry out these evaluations.

Due to safety reasons, almost 100% inspecting is the norm in the aerospace industry. Therefore, there exist inspection data, thus quantitative data. However, these data are employed mainly for process optimization and rework practices but are not used for statistical analysis during design activities and probabilistic design. The reasons for not reusing inspection data can be classified into three types of barriers: information, technical and organizational barriers, with the information barriers the key to the solution. Despite the existence of quantitative data, the information provided by current inspection data is not suitable for analysis in design activities. This problem can be broken down into four sub-problems, *why*, *what*, *how* and *when to measure*. These questions have not been properly defined in order to get the right quality data. Therefore, to produce pertinent and adequate manufacturing data to be reused in future design activities, support is needed to identify the elements within the manufacturing process that defines and affects producibility property.

The second research question (*RQ2*) aimed at that goal. First, a conceptualization of producibility has been presented. Quality and cost have been the metrics chosen by which to evaluate producibility based on the type of application focus of this research. Welded aircraft structures are products made of geometries closely linked to functionality. Thus, manufacturing variation in key product characteristics becomes a critical issue. Therefore, for this type of application, producibility criteria cannot solely rely on the time and cost spent on manufacturing and assembly but also on the quality built into the product. The main challenge then becomes to reduce quality-related failures during production, thereby minimizing rework costs. In this thesis, quality has been defined as the concept of process capability. Quality is achieved when the output variation of a manufacturing operation is within tolerance limits. Therefore, to mitigate the risk of manufacturing variation, the starting point has been to study and map the fabrication process to understand what originates variation and when and how variation is propagated. As a result, a producibility conceptual model (see Figure 24) has been proposed to represent how quality is built into key product characteristics and which are the sources of variation, operation by operation. The model works as a taxonomy to describe and classify the parameters within the manufacturing process that build quality into the product and the product characteristics that deliver final quality to the customer.

The representation provided by the conceptual model works as a basic support to the producibility assessment activities:

1) ***I**dentify* what affects producibility
2) ***M**easure* what affects producibility
3) ***A**ssess* the interaction between factors that affect producibility
4) ***P**redict* producibility

The model is a representation of how producibility gets tangible during the manufacturing process. However, the model does not prescribe how to conduct producibility assessments, which is in fact the goal of the third research question (*RQ3*). To answer this question, the Welding Capability Assessment Method (WCAM) has been proposed as a systematic approach with which to conduct producibility assessments for the particular case of welding. This step-based method uses the producibility model as a basis and presents an array of tools linked to each step for the objective of analyzing the welding operation system. First, WCAM identifies output variables (key product characteristics (KCs) and tolerance limits which define performance quality) and second, input variables (design parameters (q_{DESIGN}) that cause failure modes, thus originating variation in the KCs identified. The last step focuses on identifying sensitivity coefficients with which to relate input and outputs, thus building

producibility “rules”. Placing the focus of this research on design parameters as input variables rather than on process parameters is because the focus is on creating DFM rules. The aim is to investigate what impact the design (product structure and characteristics) has on manufacturing outcome.

The quantification of variable relationships and sensitivity coefficients within the welding system relies heavily on physical experimentation. During welding, heat transfer, melting, solidification, microstructure transformation, macrostructure discontinuities, shrinkage and distortion are some of the many phenomena that occur. In industry practice, welding simulations combined with variation simulations are extensively employed. However, not all phenomena related to welding can be virtually modelled. Furthermore, if the objective is to analyze a large number of geometrical design variants, physical experimentation can become costly, which is why sometimes structuring and automating expert knowledge is still relevant.

WCAM aims at extracting patterns and engineering rules by combining specialized information about welding problems, know-how, inspection and simulation data to understand the effect of certain design parameters (q_{DESIGN}) on the quality of welding outcomes (KCs+T). In this way, welding capability data can be built to evaluate how different product geometries, constituting the design space, will affect the output of the welding process. Combinations of of data, both qualitative and quantitative, reinforce results and strengthen the information built about process capability. With WCAM, evaluations are no longer limited to a single geometry and the study of the process parameter window. Instead, the welding capability space, meaning all geometrical variants that fulfill manufacturing quality, is assessed. This information can then be reused to optimize and evaluate trade-off alternatives in terms of producibility while exploring and analyzing the design space, as well as supporting tolerancing.

The proposed model and method establish the structure and basis for generating capability data and extracting interactive engineering rules. These results represent an advancement over traditional qualitative guidelines and expert judgments about welding difficulties and point towards a more quantitative approach, supporting virtual development in the future.

It can be concluded that results presented in this thesis 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 FUTURE RESEARCH AGENDA

In multidisciplinary design of welded aircraft structures, requirements and tolerances in design parameters need to be set not only to ensure welding output quality and producibility, but also to satisfy requirements from other disciplines such as aerodynamics, product life, product weight and cost. For instance, in the case of a guide vane in a jet engine component structure, increasing the value of the leading edge radius would decrease producibility problems. In contrast, increasing that radius would, in some cases, decrease aerodynamic performance. This is a simple example that illustrates the trade-off between producibility and aerodynamics, thus highlighting the existing conflict between the requirements of various disciplines. Thus, the welding capability space must be well understood and quantifiable to support trade-offs with other disciplines, aspects that will be studied in future research.

Future research is divided into four work packages (see Figure 33). The first and second work packages will focus on the acquisition and analysis of test, production and simulation

data to further refine research results, i.e. the producibility model and WCAM method. Simulation results will be compared to physical test/production data when applicable. Besides validating the WCAM method, the purpose is to investigate the impact of selected design parameters on welding output quality. Additional process capability data and sensitivity coefficients will be built. Other welding methods will also be selected as case studies.

The last two work packages will aim at implementing research results into industrial practice, thus into the product development process. Applicability and usefulness of the results will thereafter be evaluated. In essence, the *producibility* conceptual model together with the WCAM method and the information and rules generated about process capabilities will be fully automated and incorporated into a multidisciplinary design analysis and optimization (MDAO) environment. In this way, product variants can be evaluated quantitatively across a full range of product requirements, objectives and constrains from various disciplines. Production cost can also be included as a criterion for multi-optimization besides evaluating fabrication quality outcome and technical disciplines including mechanical and aerodynamic performances. Considering production cost together with quality would complete the concept of producibility, as defined in this thesis (see Introduction).

Furthermore, a potential application of research results that might also be explored is the support provided to welding method selection. So far, results have been attained by assuming that a welding method has already been selected.

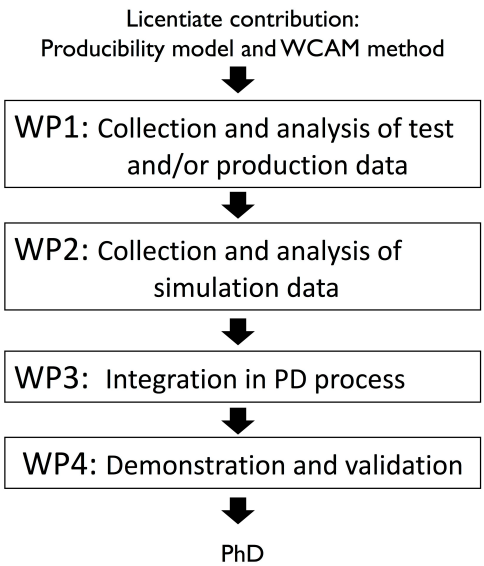

Figure 33 Future research is divided in four work packages

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