THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards a Digital Twin for Individualized Manufacturing of Welded Aerospace Structures

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Cover:
The cover illustration shows how the envisioned digital twin interacts and exchanges information with various steps of a manufacturing process for fabricated aerospace structures.

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Abstract

The aerospace industry is constantly striving towards lower fuel consumption while maintaining a high standard with regards to safety and reliability. These increasing demands require the development of new methods and strategies for efficient and precise manufacturing processes. One way of achieving this goal is fabrication, an approach where components are built by joining multiple small parts into an assembly. This brings many advantages such as more flexibility in product design, however it also adds geometrical variation to the manufacturing process which needs to be managed. Since the parts in the assembly are produced separate from each other before being joined together, issues can occur related to how these parts fit together. If a single part in the assembly deviates slightly from its intended shape, this deviation may propagate in the assembly. It may also stack with deviations in other parts. This can sometimes be difficult to predict and manage using existing manufacturing tools developed within the fields of geometry assurance and robust design.

The traditional approach to managing geometrical variation is usually based on making statistical assumptions about the variation that is going to occur in the manufacturing chain. With rising complexity in product design and increasingly tight tolerances, the traditional geometry assurance approach may not be sufficient to guarantee the high geometrical quality required from the final product. Individualized manufacturing has previously been proposed as a way of increasing the precision and reliability of a production process by treating each product individually based on its unique properties. This can be achieved with a digital twin, an emerging technology which works by creating a virtual copy of a physical process. The work presented in this thesis is directed towards realizing a digital twin for fabricated aerospace components. The first contribution is a framework describing how a digital twin could be implemented into a typical fabrication process within the aerospace industry. Since fabrication makes heavy use of welding to join multiple parts, welding simulation is an important component in this implementation. The digital twin also needs to manage measurement data collected from the parts on the assembly line, and this data should be considered within the welding simulation. The result of this simulation is then used to adapt and adjust the manufacturing process according to the conditions that have been measured and analyzed. An analysis loop is proposed in this thesis for realizing the functionality of the digital twin. A case study is conducted to evaluate the precision of the proposed analysis loop by comparing its predictions to a real welded assembly. The results of the case study show that the predictive precision of the proposed method beats the accuracy of a traditional, nominal prediction. This is an important first step towards the completion and future implementation of a digital twin for welded assemblies.

Keywords: geometry assurance, non-nominal welding simulation, digital twin

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Appended Papers

Paper A

Hultman, H., S. Cedergren, R. Söderberg and K. Wärmefjord (2020). ”Identification of Variation Sources for High Precision Fabrication in a Digital Twin Context”. ASME International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers.

Paper B

Hultman, H., S. Cedergren, R. Söderberg and K. Wärmefjord (2021). ”Towards a Digital Twin Setup for Individualized Production of Fabricated Components”. ASME International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers.

Paper C

Hultman, H., S. Cedergren, K. Wärmefjord and R. Söderberg (2022). "Predicting Geometrical Variation in Fabricated Assemblies Using a Digital Twin Approach Including a Novel Non-Nominal Welding Simulation." Aerospace 9(9): 512.

Work distribution

The papers appended in this thesis were conceptualized and outlined in collaboration with the co-authors. The main author prepared the results and wrote the original drafts of the papers. The co-authors supervised the work, and reviewed and edited the final version of each paper.

Contents

1 Introduction

In this chapter, the research topic is introduced and put into a broader context. The objective of the research as well as research questions are presented.

1.1 Towards individualized production of aircraft components

The aerospace industry is facing constantly increasing requirements on quality and reliability, and the designs are becoming increasingly complex in order to meet rising demands on low weight and fuel burn. New manufacturing methods will be necessary in order to push the limits of high precision manufacturing processes and get ready for the next generation of aircraft engines. Working towards the goal of lighter and more efficient aircraft structures, there is a growing effort to produce parts through fabrication. In this context, fabrication refers to production processes where several smaller parts are joined together through welding to create the final product. This has several advantages over the traditional method of starting with a single large casting or forging and then removing excess material, but it also introduces more variation to the process. In a fabricated assembly, the geometrical variation of every single part must be taken into account. In order to ensure a sufficiently good fit in the interfaces between the parts, many different factors have to be considered in order to calibrate the process.

This calibration procedure usually involves heavy use of geometry assurance tools, which have been developed in order to statistically estimate geometrical variation while designing a manufacturing process. However, as the requirements continue to increase, the challenge of keeping a fabrication process within tolerance becomes more difficult. At some point, it is no longer feasible to approach each individual assembly of parts with identical settings and process parameters. Small individual differences at the part level makes every assembly unique and in order to reliably achieve a satisfactory output, each assembly will require small adjustments. This is commonly referred to as mass customization, meaning that each product is approached individually rather than interchangeably. The concept of adaptive and individualized manufacturing processes have been explored in (Boorla, Eifler et al. 2018, Forslund, Lorin et al. 2018).

A key enabler of the individualized manufacturing approach is the increasing amount of data collection taking place during the manufacturing process. The measurement data collected from the production process can be used to analyze each assembly individually, rather than treating it as nominal. In combination with the increasing availability of computational power, a customized process simulation can be set up to run in parallel with the manufacturing process. This is sometimes referred to as a digital twin, which describes a system that is created in order to mirror an aspect of a physical process in a virtual environment. A digital twin for manufacturing has the potential to increase the geometrical quality of the final product by enabling an individualized approach. However, many obstacles remain before this type of system can be fully realized and implemented.

1.2 Research objective

Geometrical variation is a well-known issue within the manufacturing industry, and a wide array of tools have been developed within the field of geometry assurance to manage different kinds of variation. These tools usually rely on statistical methods where all foreseeable variation is analyzed in order to choose an ideal manufacturing concept that can produce good geometrical quality under many different circumstances. However, the concept of adaptive geometry assurance has not been explored to the same extent. Adaptive manufacturing has a low level of implementation within many advanced fabrication processes, suggesting that there is insufficient knowledge about this method. The potential for improving geometrical quality using adaptive manufacturing with digital twins needs to be investigated. Knowledge is also needed related to how a digital twin should be implemented in a high precision fabrication process.

The objective of this research is therefore to provide insight on digital twins in the context of advanced fabrication processes. The research will contribute towards finding an efficient way of implementing digital twins in this type of manufacturing process.

1.3 Scientific goal

Digital twins for manufacturing have been explored on a theoretical level (Söderberg, Wärmefjord et al. 2017). Some functionality has been demonstrated through virtual experiments, showing how a digital twin interacts with statistical variation in a simulated environment. However, little work has been done to show how a digital twin would behave in a physical manufacturing environment. In order to bridge the gap between the virtual environment and the physical environment, a better understanding is required about how the properties of a physical part should be transferred onto a virtual model and how these properties should be selected. Welding simulation plays an important role in a digital twin for fabricated assemblies. Plenty of research has been done in the field of welding simulation, however it has not taken into account the specific context of a digital twin (Söderberg, Wärmefjord et al. 2018), which includes a non-nominal simulation model and a time constraint.

The first scientific contribution of this work is therefore to provide a better understanding of how information should be exchanged between the physical process and the virtual environment of a digital twin. The second scientific contribution relates to how welding simulation should be performed in the context of a digital twin for manufacturing.

1.4 Industrial goal

From an industrial point of view, a better understanding is needed of how a digital twin can improve product quality and reduce manufacturing costs. The implementation of digital twins in advanced fabrication processes remains minimal, and geometrical variation is addressed with manual adjustments and rework. This research aims to demonstrate that a digital twin can reliably improve the geometrical quality of a fabricated product. The first step is to show that the geometrical variation of a welded assembly can be predicted based on measurement data from its individual parts. This will contribute towards the long term industrial goal of implementing digital twins in high precision fabrication processes.

1.5 Research questions

Based on the goals of the research project, three research questions have been formulated in order to guide and focus the work.

RQ1: What affects the geometric quality in a fabrication process at the individual part level?

The first research question is aimed at clarifying the context in which the digital twin will be implemented. In order to improve geometrical quality at the individual part level, the sources of geometrical variation in a fabrication process must first be clearly defined.

RQ2: How can welding simulation be implemented to create a digital twin of a fabrication process?

The implementation of welding simulation in the context of a digital twin is a crucial factor. The working conditions of a digital twin brings unique requirements on the welding simulation, including non-nominal geometrical input and significant simulation time constraints.

RQ3: How can a digital twin improve the geometrical quality of a fabricated welded assembly to support individualized manufacturing?

The final research question frames the ultimate goal of controlling the fabrication process in order to improve geometrical quality. This requires a viable solution for feeding information back from the virtual environment of the digital twin to the physical environment of the manufacturing process.

1.6 Delimitation

This research is focused on manufacturing processes that include machining, sheet metal forming, and welding. Variation sources from other manufacturing methods are not considered. The digital twin concept developed in this work is mostly relevant for products with high requirements and low production volumes, which is typical in the aerospace industry.

1.7 Structure of the thesis

In the next section, a frame of reference will be given in order to place the presented work in a larger context. Important concepts related to the research project are introduced and explained. This is followed by a section outlining the research approach. The research methodology used in this work is described, and the performed work is placed within the framework of the methodology. Next, the results of the research project until this point are presented. The results are structured into five main results, each addressing a main aspect of the work. A discussion is then presented in the following section, where the research questions are addressed based on the results. The final section draws some conclusions on the work performed until now and on the planned future work.

2 Frame of reference

The results presented in this thesis are based on several different fields of research. This chapter presents the research areas which are relevant in order to interpret the results and put them in their intended context. In this way, the results of the thesis can be framed within the existing body of knowledge. One of the main goals of this research is to study how the geometrical quality of fabricated products can be improved by individualizing the manufacturing process. The first section of the chapter focuses on the concept of geometrical variation. This term is important to define since geometrical quality is the property that this research is ultimately attempting to improve and optimize. The sections that follow are aimed at explaining the tools that are currently being used to manage the effects of geometrical variation. These tools and methods belong to the area of geometry assurance. Basic concepts such as producibility assessments, locating schemes, and tolerance management are introduced before moving on to tolerance analysis and variation simulation. Welding simulation is then introduced within this specific context, focusing on how welding affects geometrical quality and how these effects can be predicted using welding simulation. Finally, the concept of digital twins is introduced in the final section of the chapter. The digital twin paradigm is central to the results of this thesis, and this section provides some background on digital twins and how they can be applied within manufacturing.

2.1 Geometrical variation in fabricated products

The goal of the research presented in this thesis is to improve the geometrical quality of fabricated products. This section focuses on how geometrical quality is defined within the context of manufacturing and how it can be quantified. At the most basic level, the quality of a product can be described based on how it affects the end user of the product (Taguchi and Wu 1980). When the product does not perform as intended, a quality loss is incurred. Low quality therefore leads to a less desirable product. Losses can also occur during the manufacturing of the product if additional work is required due to poor quality.

Geometrical quality relates to quality aspects of a product that are purely based on its dimensions. When a product is designed and developed, it is given a set of geometrical properties that fully describe its shape and size. For example, a wheel should be round and a mirror should be flat. These are called nominal properties, and correspond to the exact shape and size intended by the designer of the product. In reality however, there is no such thing as a perfectly round or perfectly flat object, these only exist in theory. If you look closely enough at a physical object, there is always some amount of deviation from its intended shape and size. This deviation is often referred to as geometrical variation, and occurs to a varying extent in all products. The goal when manufacturing a product is therefore not to achieve a perfect result without any variation, but to ensure that the variation is small enough that it will not significantly impact the performance of the product. Depending on the environment where the product will be used, the amount of geometrical variation that can be allowed can vary from centimeters down to micrometers. A lower amount of allowed geometrical variation, and thus a higher geometrical quality, will require a more accurate and advanced manufacturing process.

The difficulty level of achieving a certain geometrical quality is based on multiple factors, including the amount of complexity in the geometry of the product, the materials, and the different manufacturing operations that are used to make it. If the product can be made from a single piece of material, the geometrical quality of the finished product will depend on how accurately this piece of material is manipulated through machining and bending to achieve the required shape. In many cases it is not feasible to make a product from a single piece of material, such as when making an engine. This means that multiple parts have to be combined into an assembly. The geometrical quality of the final product will be affected by the geometrical variation in each individual part in the assembly, leading to a more complex manufacturing process (Soderberg and Lindkvist 1999).

The process of making a product by joining an assembly of separate parts is sometimes referred to as fabrication. In a fabrication process, parts are manufactured separately and then joined into a final product (Vallhagen, Lööf et al. 2011). Welding is often used for joining the parts. Fabrication solutions are increasingly preferred for aerospace engine manufacturing (Runnemalm, Tersing et al. 2009), since they offer several advantages over starting with a single workpiece and removing material to create a product. One such advantages is the flexibility to use different materials in different parts of the component, combining suitable alloys based on requirements on strength, heat resistance, and weight. Fabrication also offers flexibility when it comes to the supply chain. Smaller parts are much easier and cheaper to source than large, high quality castings or forgings. Choosing fabrication also creates unique challenges when it comes to geometrical quality. The geometrical quality of each part in the assembly will propagate through the assembly and stack with the variation in other parts (Forslund, Söderberg et al. 2011). In a large assembly with multiple parts, the stacking phenomenon can be difficult to predict and manage. Every assembly will have a unique combination of geometrical deviation in its parts. This challenge is made even more complex when welding is used to join the parts, since welding induces deformation and stresses in the material that adds further geometrical variation to the final product. In order to manufacture a fabricated component that conforms to the high quality requirements common within the aerospace industry, these effects need to be anticipated and managed.

2.2 Robust design and producibility assessments

As mentioned in the previous section, all production processes contain some amount of geometrical variation. A perfect nominal process only exists in theory, in practice the geometrical variation can be reduced but not eliminated (Forslund 2016). Since it is not possible to completely eliminate all variation in a process, the best strategy is instead to design a process that can produce an acceptable product even though some given amount of geometrical variation is present. Several approaches have been developed towards this goal. This is referred to as robust design, since the process and thereby the product is made robust towards variation (Boorla, Eifler et al. 2018). Due to the random nature of variation, in order to be robust the process must be designed to function under a broad array of conditions. These conditions need to be anticipated by the designer of the process.

A production process can be described with a block diagram (Phadke 1995) as shown in Figure 1. All processes have an input which is transformed by the system into an output. The input consists of a single part or an assembly of parts which are being modified or joined. In theory, a given input will always yield the same output based on system parameters which remain constant. In practice, there is always some amount of random variation in the system which causes the output to vary. This variation can come both from variation in the parts used as input, or from variation in the process itself. In this model, unknown and random variation is referred to as noise factors. In a production process there are also some settings and parameters that can be controlled by the operator, here referred to as control factors. The basic idea of robust design is to set the control factors so that the influence of noise factors on the output is minimized.

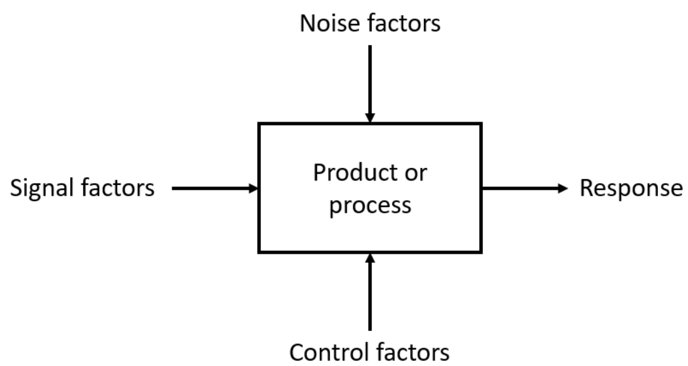

Figure 1: Modelling a process with a block diagram as proposed in (Phadke 1995)

It has been suggested that the challenges related to geometrical quality in fabricated components require a more holistic approach that considers these issues as early as during the design phase (Boorla, Eifler et al. 2018). The producibility of a component can be defined as the capability to meet design specifications in a robust and efficient way (Madrid, Söderberg et al. 2016). By analyzing the combination of a product system and a production system, conclusions can be drawn about how robust it will be (Wolff 2014). This can be done at an early stage in the product development process, making it possible to predict the robustness of different combinations of design concepts and production methods. Certain design features may be more compatible with a specific manufacturing method, leading to an overall increase in final product quality. Within the research field of producibility, frameworks and models have been developed that help the designer make design decisions early in the product development process (Madrid 2020). These tools provide guidance on how to select a design concept and a production system that maximizes the robustness of the manufacturing process (Vallhagen, Isaksson et al. 2013, Vallhagen, Madrid et al. 2013).

2.3 Locating schemes

Locating schemes are used to position the parts during all operations that they go through the manufacturing process. Before any operation or measurement of a part can take place, the part must be positioned using a fixture. If the part is not positioned in the same way during each consecutive operation, variation will be added to the process. The design of the locating schemes is therefore foundational for the robustness of all manufacturing processes (Söderberg and Carlson 1999).

The purpose of the locating scheme is to lock a part in all six degrees of freedom and fully prevent it from moving around. A basic and commonly used approach is the 3-2-1 locating scheme (Söderberg, Lindkvist et al. 2002). Three points on the surface of the part are locked in the X direction, making up the primary datum plane and preventing the part from moving along the X axis as well as rotating around the Z and Y axes. This essentially means that the part is now only free to move around on a plane that is orthogonal to the X axis. The next step is to add two points on the part and lock them in the Y direction. This prevents the part from moving along the Y axis, and it can no longer rotate around the X axis. The part is now only free to move along the Z axis, and the only thing remaining to complete the 3-2-1 locating scheme and fully locking the part is to add one more point and lock it in the Z direction. With these six points, the position of the part has been fully defined. For compliant, non-rigid parts, the locating scheme may require additional locators or supports in order to prevent deformation due to external forces such as gravity. Sheet metal parts are a common example, being highly susceptible to deformation due to their thinness. The N-2-1 principle has been proposed for such cases (Cai, Hu et al. 1996), constraining the sheet metal part with $N \geq 3$ locators on the primary datum plane.

The directions for locking the parts in a locating scheme does not have to be fully orthogonal, and the number of points on the surface can be reduced to three by locking these points in multiple directions. Different types of locating schemes have been defined and proposed depending on the requirements of the process (Söderberg, Lindkvist et al. 2006, Söderberg, Lindkvist et al. 2006, Söderberg, Lindkvist et al. 2006). However, regardless of the type of locating scheme, the points chosen for the locating scheme will be subject to some amount of variation. This can be caused by variation on the surface of the part itself, and it can also occur due to variation in the contact points of the fixture that is holding the part. In order to increase the robustness of the process, the locating scheme must be chosen so that the influence of this variation on the positioning of crucial surfaces is minimized. For example, in a machining operation it is important that the machined surface does not move.

2.4 Tolerance management

The amount of variation that is allowed in the manufacturing process can be controlled through tolerance allocation (Morse, Dantan et al. 2018). Each surface and feature on a part is given a tolerance, an accepted interval within which the surface is allowed to vary. If the surface is outside of this interval, the part needs to be scrapped or reworked. Tolerancing is an important part of the design process, since it controls both the precision and the producibility of the final product. A production process with forgiving tolerances will be easier to set up and run, but the geometrical quality in the final product will be lower. If the tolerances are more demanding, the requirements on the manufacturing equipment will also go up. Research within the field of tolerancing has previously been reviewed in (Hong and Chang 2002).

Application of tolerances to a product system can be done with either a top-down or bottom-up approach. When using the top-down approach, the requirements on the final product are used as a starting point. The tolerances that are needed in the final product are then broken down into tolerances on separate parts in the assembly. An advantage in this approach is that tighter tolerances can be applied to specific surfaces in the assembly that correspond to those surfaces on the final product which are subject to the highest requirements. Wider tolerances can be applied on other, less critical surfaces to reduce cost. The top-down approach has been investigated in (Söderberg 1993, Söderberg 1994, Söderberg 1995, Lööf 2010). In the bottom-up approach to tolerancing, the tolerances on individual parts are used as a starting point. Each tolerance is applied based on standards or experience and knowledge regarding the manufacturing process capability for each individual part in the assembly. The tolerances on the final product becomes a result of these individual tolerances. A hybrid approach can sometimes be used which combines bottom-up and top-down in order to take both final product requirements and process capability into account.

When the locating scheme for a part has been decided, the tolerance of each locating point will affect the deviation of the part. If multiple parts are assembled into a final product, the challenge of tolerance management becomes even more complex. In an assembly, the positioning of each part depends on the contact surfaces of adjacent parts. The geometrical variation of adjacent surfaces will propagate to the next part since the positioning is affected. In a worst case scenario, the geometrical variation in the parts will stack and propagate, which may severely reduce the geometrical quality of the final product. This is an important problem to take into account when designing an assembly and allocating tolerances (Lööf, Hermansson et al. 2007). In order to analyze geometrical quality in an assembly, variation simulation can be applied.

2.5 Statistical tolerance analysis

In order to predict the outcome of a process with random variation, engineers rely on statistical analysis. As previously mentioned, all properties of a manufactured component are subject to some amount of variation. A common assumption in industrial processes is that these product properties will vary according to a normal distribution (Chase and Parkinson 1991). A normal distribution is a continuous probability distribution that can be described as

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where μ is the mean value of the distribution and σ is denoted as the standard deviation. According to the central limit theorem, if repeated samplings are made from a distribution with finite mean and variance then the mean values of the samplings will be distributed according to a normal distribution (Evans 1975). As a consequence, any value which can be described as the sum of multiple independent processes can be expected to have a normal distribution. This definition includes all physical properties of a manufactured component. As the manufacturing process is repeated for each individual product, the behavior of most product properties over time will converge towards a normal distribution with a certain mean value μ and standard deviation σ. The mean value should ideally be equal to the desired value of the product property, and the standard deviation defines the variance of the property. A high standard deviation means large variance, leading to more variation between products over time. The standard deviation should be small enough to ensure that this value stays within an acceptable margin of error for a reasonable share of the total amount of manufactured products.

Since a normal distribution curve can be used to model how a product property or measure varies in a population of products, this curve can also be used to predict the percentage of products for which this specific measure will be within the allowed tolerance limits. The six sigma toolbox has been developed to help engineers quickly analyze and evaluate the performance of a manufacturing process (Taguchi, Chowdhury et al. 2004). The expression six sigma comes from the classification of a manufacturing process for which the tolerance limits are equal to three standard deviations on both sides of the mean of the standard distribution curve for that process. This means that more than 99.9997% of manufactured products over time can be expected to meet that specific tolerance limit. The process capability index has been developed as a way of quickly quantifying the performance of a process (Taguchi, Chowdhury et al. 2004). It is defined as

$$C_p = \frac{USL - LSL}{6\sigma}$$

where USL is the upper tolerance limit and LSL is the lower tolerance limit. This expression does not take into account whether the mean of the process is centered between the upper and lower limit, meaning that a manufacturing process with low variance can have a high C_p even though the process is not properly calibrated and centered between the upper and lower limit. The adjusted capability takes this factor into account, and is defined as

$$C_{pk} = min\left\{\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\}$$

where the mean μ is now included in the expression. To achieve a high C_{pk}, the manufacturing process must both have a low variance and be centered between the upper and lower tolerance limits. By modeling the output of a process as a normal distribution, an engineer can quickly measure its performance by using the C_p and C_{pk} indicators. C_{pk} = 2 corresponds to a six sigma process with 99.9997% yield, while C_{pk} = 1.33 corresponds to a process with a 99.99% yield.

The capability index is valid for a single property or dimension after a specific manufacturing operation. However, a product is usually made using a series of manufacturing processes and large or complex products are often assembled from multiple joined parts. This means that the quality and geometrical variation in the final product will be affected by the interaction of multiple individual properties, each having a unique normal distribution. Modeling the quality of a final product therefore becomes more complex than modeling the variation of a single property or process. The field of tolerance analysis has been treated in (Chase and Parkinson 1991, Nigam and Turner 1995, Gao, Chase et al. 1998, Hong and Chang 2002, Shah, Ameta et al. 2007). For a simple linear stack-up, the assembly response Y can be expressed as

$$Y = a_0 + a_1X_1 + a_2X_2 + \ldots + a_nX_n$$

where a_i are constants and X_i are stochastic variables that represent different sources of variation in the assembly, such as the exact position of different contact surfaces. In this case, the mean μ_Y and the standard deviation σ_Y of the assembly response Y can be calculated as

$$\mu_Y = a_0 + a_1\mu_1 + a_2\mu_2 + \ldots + a_n\mu_n$$
$$\sigma_Y{}^2 = a_1{}^2\sigma_1{}^2 + a_2{}^2\sigma_2{}^2 + \ldots + a_n{}^2\sigma_n{}^2$$

where μ_i and σ_i are the mean and standard deviation of the individual stochastic variables X_i. If the response function is approximately linear, it can be linearized with a Taylor expansion (Evans 1975). If the response function cannot be expressed linearly, an extended Taylor series expansion can be used to estimate the mean and standard deviation. The assembly response can be approximated by up to a sixth order Taylor series expansion as

$$\begin{aligned} Y &= f(\mu_1, \mu_2, \ldots, \mu_n) + \sum_a (X_a - \mu_a) f_a \\ &+ \frac{1}{2!} \sum_{ab} (X_a - \mu_a)(X_b - \mu_b) f_{ab} + \ldots \\ &+ \frac{1}{5!} \sum_{abcde} (X_a - \mu_a)(X_b - \mu_b)(X_c - \mu_c)(X_d - \mu_d)(X_e - \mu_e) f_{abcde} + O[(X - \mu)^6] \end{aligned}$$

where f_a, f_{ab} and so on are partial derivatives of f with respect to X_a, X_b and so on. Partial derivatives are evaluated at $X_i = \mu_i$. The last term includes all neglected terms of higher order.

The calculation of this type of Taylor series can be a complex and time-consuming task, and the analytical approach is therefore not always ideal when modeling an assembly response. An alternative is to use a numerical approach with Monte Carlo simulations. This method is more computationally heavy and demanding (Nigam and Turner 1995), since it involves generating a large number of samples with different part tolerances. In each iteration, each part tolerance is generated from its corresponding probability distribution and the assembly response is calculated with this set of tolerances. By repeating this process a large number of times, a probability distribution is generated for the assembly response.

2.6 Variation simulation

Robustness can be increased by considering how the points of the locating scheme are placed on the part. If the points are close together, the positioning of the part will generally become less stable and more sensitive to variation. Depending on the tolerances allocated to these locating points, the positioning of the part may become unstable. Variation simulation can be used to quickly analyze these effects. By creating a virtual model of a part, different locating schemes can be applied in the virtual environment to assess different effects on part positioning (Söderberg, Lindkvist et al. 2006). The tolerances of the locating points can also be adjusted to analyze the effect on final geometry.

In reality, geometrical variation is always random. Before the process starts, the only thing that can be known about the variation in a properly managed process is that it will be within the tolerances that have been allocated to each surface. Variation that is outside of the assigned tolerances will be taken care of during inspection before the process starts, leaving only an allowable amount of variation in the part. This allowable range of variation is used as an input to the variation simulation. Once this range has been set, the variation within the range has to be considered as random. A common approach for modelling this random variation is by using Monte Carlo simulations. Monte Carlo methods rely on generating a large number of outcomes based on some preset conditions. In this case, the preset conditions are the locating scheme and the allocated tolerances in each locating point. Each Monte Carlo iteration generates a random process outcome based on this input, showing a possible result from the modeled process. By generating a large number of process outcomes and compiling the results, the process can be assessed and analyzed based on different types of measures.

The first step of the analysis process is to decide on what to measure on the part or assembly. This choice will depend on the properties of the final product. Some surfaces may be important to the performance of the product, and others may simply be important to the perceived quality of the product (Stylidis, Wickman et al. 2020). In cases where the part belongs to a larger assembly, special attention must be paid to the variation in the surfaces that comes into contact with other parts in the assembly. Creating a virtual assembly in a variation simulation tool can be very helpful since this makes it possible to analyze how variation will propagate between parts and affect the geometrical quality of the final product.

Once a set of critical measures have been selected, the geometrical accuracy of these selected points can be assessed by generating a large number of simulated process outcomes. This outcome is then compared to the upper and lower design limits of the critical measure, showing how many parts from the simulated outcome that have cleared the design limits and how many parts have that have failed to meet requirements. If the number of failed parts is deemed too high, the tolerances of the locating points can be tightened. Tightening a tolerance costs money, and should not be done without careful consideration. In this scenario, a contribution analysis can be helpful. For each critical measure, the software can calculate how sensitive this specific measure is to variation in each of the locating points of the part. Tolerances can then be tightened in the locating points that contribute the highest amount of variation to the critical measures. In this way, a variation simulation can be used to optimize a process based on random variation within the allocated tolerances.

2.7 Compliant variation simulation

In the previous section, all parts in the variation simulation were considered to be fully rigid. This means that they do not deform when external forces or pressures are applied. It also means that they are not affected by the internal stress state in the material of the parts. By making this simplification, variation simulation becomes quicker and less computationally heavy. However, it also less accurate and less true to the physical process that is being modelled. In reality, all parts are subject to some amount of deformation. In some cases this is easy to observe, for example a large piece of sheet metal can become noticeably deformed simply through the force of gravity that weighs the sheet down in points where it is not properly supported. Residual stress in the material can also be induced by processes such as machining (Zhang, Wang et al. 2014). For all physical parts, the total deformation is the result of an equilibrium between external forces and in the internal stress state of the part. These effects can be taken into account by conducting variation simulation with a non-rigid model (Söderberg, Lindkvist et al. 2006).

In order to create a non-rigid model, the finite element method (FEM) is applied. A virtual model that describes the geometry of the part is divided into small elements. Each element has a simple geometry that is described with a set number of flat surfaces and straight edges. This makes it possible to describe the stress state of each small element with simple terms, and the simple geometry also makes it possible to connect each element to its neighbor. Using these elements as building blocks, the complete physical part can be reconstructed in a virtual environment. The fidelity of the model depends on the size of the elements, smaller elements create higher fidelity to the real part but is also heavier to compute. In each case, a balance must be struck between the resolution of the mesh and the speed of the computation.

Once a mesh has been created that describes the physical part, external forces can be applied either as forces acting on a single nodes or as pressures spread out across multiple nodes in the mesh. These external forces can be generated by the fixture that is used to mount and fixate the part before the process, or by the forces applied from tools during the process itself. As previously mentioned, forces are also generated by the force of gravity that acts on the mass of the part. These external forces form an equilibrium. The interaction between multiple parts in an assembly will also become more complex, and contact modelling has been added to variation simulation for this reason (Dahlström and Lindkvist 2007, Wärmefjord, Lindkvist et al. 2008, Wärmefjord, Söderberg et al. 2016). In order to decrease the computation time for compliant variation simulation for assemblies, the Method of Influence Coefficients (MIC) has been suggested where a linear relation is derived between part variation and assembly variation

(Liu and Hu 1997). For a rigid part, the six locating points are sufficient for keeping the part in place but when the part is allowed to deform, additional support may be required in order to counteract the force of for example a drill pushing against the part. The fixture becomes more complex, consisting of a N-2-1 locating scheme (Cai, Hu et al. 1996) with additional supports and clamps.

As the external forces act on the part, it will start to deform. In general, a small deformation will cause elastic deformation in the part, meaning that the part will return to its original shape like a rubber band once the forces are removed. However, as deformation of the part continues to increase, it will go over from elastic deformation into plastic deformation. Plastically deformed parts do not return to their original shape when external forces are removed, instead they retain their new deformed shape. This effect is used in sheet metal forming in order to give a piece of sheet metal a new shape by applying a large deformation. Since a plastically deformed part also contains an amount of elastic deformation that wants to return to its original state, the conflict between plastic and elastic deformation in the part will create internal stresses in the part. These internal stresses are often referred to as residual stress, and will remain in the part after the process is finished. This will either have an effect on the next consecutive manufacturing process that the part goes through, and at the end it may become a part of the final product and affect its performance. Residual stress can be affected by multiple factors including machining (Zhang, Wang et al. 2014), welding (Lorin, Cromvik et al. 2015), and forming (Steffenburg-Nordenström and Larsson 2014), and can therefore vary between individual parts.

2.8 Thermal effects in variation simulation

Until now, it has been assumed that the part has a uniform temperature that is equal to the temperature of its surrounding environment. Changes in temperature causes the material to shrink or expand. This effect will vary depending on the type of material. A change in temperature will also affect the rigidness of the material (Dong, Song et al. 2014), as the part will become slightly softer at higher temperatures. There are many manufacturing processes that generate a significant amount of heat in the part. Heat can be created by friction between the tool and the work piece. This is a common effect during machining and drilling, where the tool will often reach intense temperatures (Ramesh, Mannan et al. 2000). The influence of heat treatment was investigated in (Sagar, Wärmefjord et al. 2019).

An even more extreme example of temperature-altering processes is welding. A welding process is specifically designed to add heat to the material of the part in order to melt it, so that the part can be joined to an adjacent surface. Besides from the desired effect of joining, a welding operation can have several unintended effects on the part (Madrid, Lorin et al. 2019). The heat from the weld gun is added to a small surface on the part, causing high temperature gradients. Having an elevated temperature in a small area of the part means that the material will expand and soften in concentrated areas. This has an effect on the internal stress state of the part (Dong, Song et al. 2014). The area that is completely melted, referred to as the weld seam, will shrink as the material cools and solidifies. In some cases, these effects need to be taken into account in a variation simulation (Lorin, Cromvik et al. 2015). This requires welding simulation to be included, adding the possibility to change the temperature and model how it affects the part.

2.9 Welding simulation in the context of variation simulation

The goal of a welding simulation is to calculate the changes to geometry and internal stress state that occurs during a welding. A welding simulation needs to take several factors into account, including heat distribution and structural mechanics (Lorin, Cromvik et al. 2014). During a welding process, a weld gun is swept along the interface between two parts, adding heat that melts the material and fuses the two parts. This leads to expansion in the material as heat is added, followed by shrinkage as it cools and solidifies.

To avoid problems related to quality and tolerances, welding simulation is used in order to calculate the distortion and residual stresses that remain after a welding process. Structural mechanics and heat distribution as well as the micro structure of the material are all affected by welding. For the application presented in this thesis, the deformation of the part is the main focus and it has been shown that the micro structure of the material can be ignored in these cases (Lindgren 2002). The simulation needs to model the transient temperature field, which drives changes to the structural mechanics of the welded part (Goldak and Akhlaghi 2005). For each time step, the temperature is calculated separately. A structural analysis is then performed in order to calculate the deformation of the material in response to the temperature changes. A double ellipsoid is often used for modelling the heat flux form the weld gun (Goldak and Akhlaghi 2005). This model consists of two ellipsoids which are placed in front of and behind the heat source. The double ellipsoid can be fitted to experimental outcomes, and has been designed to give an accurate structural response. In order to perform a full transient welding simulation, a calculation is first done to predict the heat distribution in each time step using a model of the heat source. The mechanical response in each time step is then simulated using this heat distribution. In this way, a welding simulation can predict the stresses and deformation that will occur in the material during welding.

As previously mentioned, variation simulation normally depends on the Monte Carlo method and aims to generate a high number of random outcomes. Welding simulation is often a computationally heavy process. The mechanical response to the added heat is calculated for each time step in order to fully capture the physical process. This procedure has to be repeated for each Monte Carlo iteration, meaning that the iterative nature of both the welding simulation and the Monte Carlo method are compounded. The result is an extremely time-consuming simulation, which may be unfeasible depending on the use case. This has led to the development of faster and more efficient welding simulation methods aimed specifically at variation simulation scenarios (Lorin, Cromvik et al. 2014).

In order to achieve a faster and more efficient welding simulation, different approaches have been developed. One approach is to perform an elasto-plastic analysis on a segment of the weld in order to obtain the equivalent elastic strain. The strain is then applied along the entire length of the weld (Ueda and Yuan 1993). This method is referred to as Inherent Strain. It has also been suggested that the distortion caused by welding can be predicted with a simplified analytical model (Camilleri, Comlekci et al. 2006). Yet another type of approach proposes that distortion can be calculated by relating it to the contraction as the melted material cools and solidifies. This has been proven to yield good experimental results, and is referred to as the Volumetric Shrinkage method (Bachorski, Painter et al. 1999, Sulaiman, Manurung et al. 2011). It is also compatible with geometric variation in the weld interface, which has led to an implementation of Volumetric Shrinkage into the SCV (Steady-state Convex hull Volumetric shrinkage) method. SCV has been developed in order to yield a fast welding simulation that takes geometrical variation into account (Lorin, Cromvik et al. 2014). It consists of three steps: first the thermal distribution in the part is calculated with a steady state computation, followed by a computation of a 2D melted zone, and finally an application of thermal loads on a full 3D model. Since the mechanical response does not have to be calculated at each time step, the SCV method is much faster than a full transient simulation. By dividing the weld seam into segments with separate 2D melt zones, accuracy can be improved for complex welds involving strong curvatures or varying wall thickness. The robustness of the SCV method was examined in (Lorin, Cromvik et al. 2014), and the possibility of splitting the weld seam into multiple segments with different melted zone profiles was shown in (Lorin, Cromvik et al. 2014).

2.10 Digital twins for manufacturing

Even with the inclusion of faster welding simulation methods, a non-rigid variation simulation including temperature effects becomes computationally heavy. Since variation simulation depends on the Monte Carlo approach requiring multiple iterations, there is a limitation to how many iterations that are feasible in an analysis using random inputs. The goal of variation simulation is to analyze as many cases as possible, where each case represents a potential combination of random geometrical variation that might appear during production. In this way, the production process can be made robust towards many types of variation so that the final product retains good geometrical quality under as many different kinds of scenarios as possible. When a product finishes the design phase and enters the production phase, it becomes possible to measure and collect data from the parts that are entering the process. The geometrical variation that has been modelled as random during the design phase now becomes knowable, making it possible to run a variation simulation with real part data instead of random variation. Since multiple Monte Carlo iterations are no longer needed, the conditions for the simulation may now allow for a higher level of complexity and detail.

A system like this is sometimes referred to as a digital twin. The idea was originally suggested by NASA, intended for application in an aeronautical context (Glaessgen and Stargel 2012). The basic concept is a virtual model which is able to mirror a physical system by using measurement data collected in real-time from the active system. In this way, a digital twin can predict the behavior of a system such as an aircraft component based on measurements of the loads that it has been subjected to, instead of using predicted loads based on worst-case scenarios such as severe turbulence or hard landings. The basic idea is thus to replace statistical life-cycle predictions with actual measured data as it is collected from the physical system. This leads to an improved and more accurate prediction of various system properties. Since this original proposition, the implementation of digital twins have been suggested for a wide range of use cases (Tao, Zhang et al. 2018). One of the areas where research on digital twin implementation is currently ongoing is within production engineering (Schleich, Anwer et al. 2017, Söderberg, Wärmefjord et al. 2017, Söderberg, Wärmefjord et al. 2018), where the goal is to set up digital twins which mirror different aspects of a manufacturing process by collecting measurements from parts and equipment (Wärmefjord, Söderberg et al. 2017, Zhou, Zhang et al. 2020). Various tools can then be used to adjust and improve the process (Schleich, Dittrich et al. 2019). Welding has been suggested as an area where a digital twin could be implemented in order to manage variation (Roy, Mishra et al. 2020).

A digital twin for manufacturing can be categorized in different ways, depending on what type of equipment is available during the process. It has been proposed that digital twins should be defined by the amount of integration to the physical system that is being mirrored (Kritzinger, Karner et al. 2018). According to this categorization, the most basic level of integration is a digital object that requires information to be transferred manually to and from the physical object. A lot of manual work will be required to achieve the required feedback loop between digital and physical object. This is referred to as a digital model.

The second type of categorization in (Kritzinger, Karner et al. 2018) is a system in which the information transfer from the physical object to the digital object happens automatically. This flow of information ensures that the digital simulation follows the physical process in real-time, as information is directly transferred and implemented into the simulation. This type of system is referred to as a digital shadow, and has more advanced requirements on the manufacturing infrastructure than a digital model.

The final level to this categorization system is a digital object that both receives and sends information automatically (Kritzinger, Karner et al. 2018).

This level of integration allows the system to automatically receive data, analyze it, and directly control the physical process. A feedback loop is created that can control and optimize the production process. This is referred to as a digital twin. By achieving an automatic flow of information in both directions, the digital twin can react immediately to any measurable change in the physical process. These changes can be analyzed to calculate a response, which is sent directly back to the physical process.

From this categorization, three main functions can be identified in a digital twin. First is the model itself, consisting of a virtual representation of the physical process that can be adapted according to measurement data in order to become more accurate. This model can be created during the design phase as the product and manufacturing process are being developed (Söderberg, Wärmefjord et al. 2017). Second is the flow of measurement data going from the physical system to the digital twin, which can be either manual or automatic. A strategy for providing a digital twin for geometry assurance with inspection data from the manufacturing process was presented in (Wärmefjord, Söderberg et al. 2017). Finally, there needs to be a flow of information from the digital twin back to the physical process during manufacturing. The production process should be updated in some way in accordance with the analysis carried out within the digital twin. A set of tools for improving the geometrical quality was presented in (Söderberg, Lindkvist et al. 2016).

3 Research approach

This chapter describes the chosen research approach and explains how the performed research work leads towards a measurable impact within the field.

3.1 Research framework

The research presented in this work has its foundation in a pronounced need within the industry, in this case high precision fabrication. The purpose of the research is to provide knowledge to support engineers in the design of production systems, with a specific focus on improved geometric quality. Apart from the industrial need, an identified research challenge is required that points to a gap within the existing knowledge in the context of the industrial need. When a need and a related knowledge gap has been laid out, a research idea can be formulated containing a strategy towards filling the knowledge gap with new learnings. This process requires a clear framework in order to structure the research and help the researcher define tasks and objectives. One such framework is Design Research Methodology (DRM), which has been proposed in (Blessing and Chakrabarti 2009). DRM is, as the name implies, used for conducting design research. The authors refer to design as activities that develop a product from a need or idea, and design research as the formulation and validation of models and theories that can form a support to improve the practice of design. This makes DRM well suited for the purpose of researching support for engineers designing production systems. DRM is a clearly structured and rigorous methodology with plenty of tools to aid the researcher in defining and conducting research activities, and has been chosen as the main framework for the research presented in this thesis.

3.2 Design Research Methodology

The main workflow of DRM is divided into four phases: Research Clarification (RC), Descriptive Study I (DS I), Prescriptive Study (PS), and Descriptive Study II (DS II). An overview of the DRM framework showing the workflow and deliverables can be seen in Figure 2.

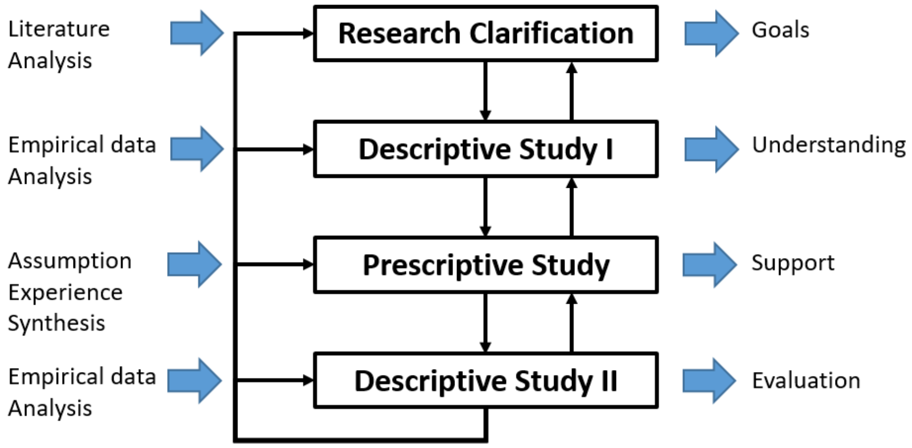

Figure 2: Main workflow of DRM, redrawn from (Blessing and Chakrabarti 2009)

The first phase is Research Clarification, which aims to help the researcher understand the context in which the support is intended to operate. This includes identifying the goals that the research should contribute towards, the main problems that need to be addressed in order to get there, and the relevant areas that need to be reviewed. This is done by establishing preliminary criteria for success, as well as an Initial Reference Model and an Initial Impact Model. These models are a core part of the methodology as they show the cause and effect chain from the Key Factor that the research is meant to influence, to the Success Factor that should be improved in order for the research to be considered successful. The Reference Model shows the current state and the Impact Model shows the desired future state where the research has been implemented. This helps the researcher to decide what factors should be the focus of the research project.

Once this focus has been established, the next phase is Descriptive Study I. Here, the focus is to elaborate the description of the existing state as shown in the Initial Reference Model and develop that model using empirical data and further analysis. The goal is to develop the Reference Model enough to provide a clear indication of how to develop a support that can improve the problematic situation by addressing key factors. During this phase, the preliminary criteria is developed into Success Criteria and Measurable Success criteria. A distinction is usually necessary between the two since the actual Success Criteria often cannot be evaluated within the scope of the research project, in which case a Measurable Success Criteria is required which can instead be used to indicate the success of the research.

The existing situation and the key factors to address have now been defined and the researcher moves on to the Prescriptive Study phase. Using the Reference Model and the Initial Impact Model, the desired situation is described in detail resulting in an Impact Model. The support that the researcher proposes for realizing the desired situation is defined and develop to an extent sufficient for evaluation against the Measurable Success Criteria. There is usually a difference between the Intended Support that the research envisions, and the Actual Support that can be developed within the scope of the project. To complete the Prescriptive study phase, the Actual Support is evaluated for internal functionality and consistency.

The final phase is Descriptive Study II, where focus lies on evaluation of the developed support. This includes identifying whether the support works as intended and has the expected effect on key factors. The researcher also investigates the need for future improvement and elaboration of the research, and evaluates the assumptions made in early stages of the project.

As shown in Figure 2, the four phases of DRM are cyclical in nature. Once a cycle is complete, the researcher can collect the learnings and restart the first phase with new objectives and goals. It can also be necessary to backtrack to a previous phase if new findings contradict earlier assumptions in a way that significantly impacts the trajectory of the project. A study does not need to contain all phases and can instead focus on specific phases when necessary.

3.3 Applied research approach based on DRM

The research process began with a literature study, used as a basis for the RC phase. Existing research within the area of digital twins for production processes was collected and combined with work experience within the industry to understand the context of the research challenge. This resulted in an Initial Impact Model which can be seen in Figure 3: Initial impact model, showing a problematic situation where fabrication is giving rise to increased geometrical variation leading to higher amount of rework and longer production time, in the end influencing profit. The preliminary success criterion is identified as decreased geometrical variation in the final product.

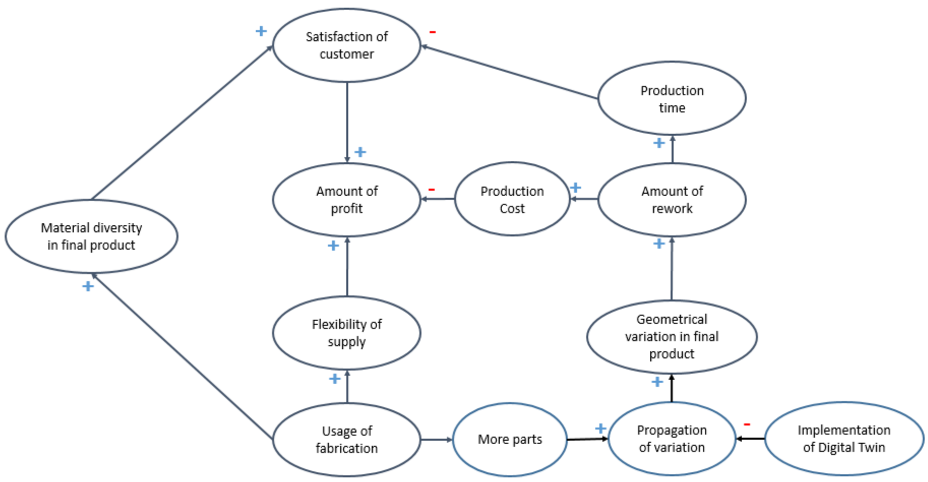

Figure 3: Initial impact model

Following the RC phase and literature study, research questions were formulated to direct the planned research work towards the identified goal. Paper A focused on creating a better understanding of the problem, thus contributing to the DS I phase according to the DRM workflow. Paper B and Paper C then began the work of developing a support in the form of a digital twin to improve the identified problems. The welding simulation module of the support was evaluated for consistency and reliability. The remaining work of the research project mainly consists of finishing the support system and evaluating it in an application. The research plan comprising three papers is summarized in Table 1.

Table 1: Research plan

Papers	**RQ**	**RC**	**DS I**	**PS**	**DS II**
Paper A	RQ1	○	●	○	
Paper B	RQ2		○	●	
Paper C	RQ2, RQ3		○	●	
●*: High contribution* ○*: Low contribution*					

3.4 Methods used in the study

As previously mentioned, a literature study was conducted in order to get an understanding of the existing body of knowledge. This includes both published scientific articles within the research field and experiences from the industrial context. From the current state of the art, knowledge gaps can then be identified which need to be explored in order to meet the research challenge.

In order to evaluate and test the support developed in order to solve the identified problems, a case study was set up. The study consisted of a small scale manufacturing process in a lab environment. Although the manufactured parts have a simplified geometry compared to real products, the basic manufacturing challenges regarding geometric variation are similar. This makes it possible to make a preliminary evaluation in the experimental environment before finalizing the support for implementation in a realistic environment for final evaluation and validation.

4 Results

The main workflow of this thesis project started with a clarification of how the digital twin should be implemented. Paper A presented a mapping of how variation occurs and propagates in a fabrication process, as well as a framework for how a digital twin could interface with the process. This served as a part of the Descriptive Study I according to the Design Research Methodology, helping to further define the context in which the digital twin would operate. This basic framework led to the proposition of an analysis loop for a digital twin along with suggested tools and methods for implementing the analysis loop in a fabrication process. In Paper B, functionality for a digital twin was presented along with results from a case study where test manufacturing in a lab environment was used in order to evaluate the digital twin. This contributed to the Prescriptive Study, testing the internal functionality of the support being developed in the research project. Paper C continued the evaluation and analysis of the proposed digital twin system, presenting detailed comparisons between simulation results and real results from the test manufacturing process in the case study.

In this section, the results of the research carried out until this point are summarized and presented. The section is divided into five main results that contribute towards the end goal of the research project, which is to implement a digital twin in a fabrication process. The relation between the appended papers and the results presented in this section can be seen in Table 2.

Table 2: Relation between appended papers and results

Papers	Result 1	Result 2	Result 3	Result 4	Result 5
Paper A	●	○			
Paper B	○	●	○	●	
Paper C			●		●
●*: High contribution* ○*: Low contribution*					

4.1 Result 1: Digital twin implementation in a fabrication process

The first step was to analyze the specific manufacturing environment where the digital twin is planned to be implemented. Since the ultimate goal is to reduce geometrical variation in a fabrication process, one of the most important aspects to consider is factors that affect geometrical quality. These factors can be divided into those that add noise and random variation to the process and those that can be directly controlled by the operator. Furthermore, there is also some amount of variation in the workpieces that enter the process. This can be visualized with a block diagram, seen in Figure 4.

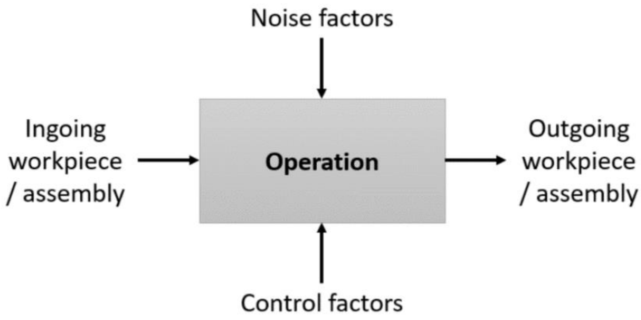

Figure 4: Block diagram visualizing the factors that affect geometrical variation in the output of the process

When the workpiece enters a process, it comes with some amount of geometrical variation. Different types of variation will affect the output in different ways. The geometrical variation in the part may affect the process in a complex way if it occurs near the locating points or assembly interfaces. The internal stress state of the part may also affect the process, especially if it involves heat which relaxes the material and allows stresses to release and cause deformation. The material characteristics of the part can have a significant influence in processes with very high requirements on precision. Characteristics of the workpiece that may affect geometrical variation are summarized with an Ishikawa diagram in Figure 5.

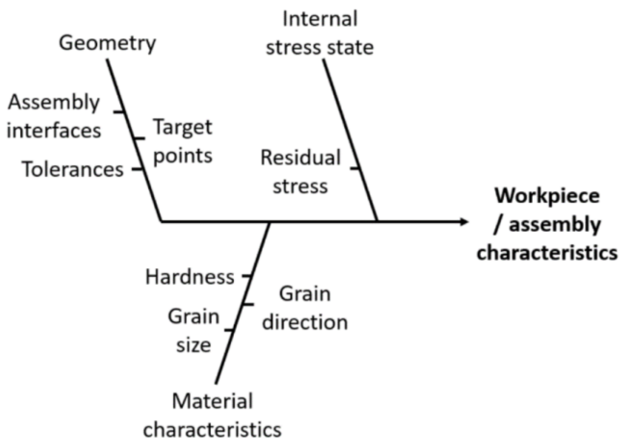

Figure 5: Ishikawa diagram showing workpiece characteristics in fabrication processes

During any manufacturing operation, there is random noise in the process that affect the output. Even if the workpiece entering the process is assumed to be perfect and completely free from defects, the result of the process will still have some defects. Different types of operations are affected by different types of noise, and the amount of variation will also depend on the process. The noise factors that are encountered in operations typical to a fabrication process are summarized in Figure 6.

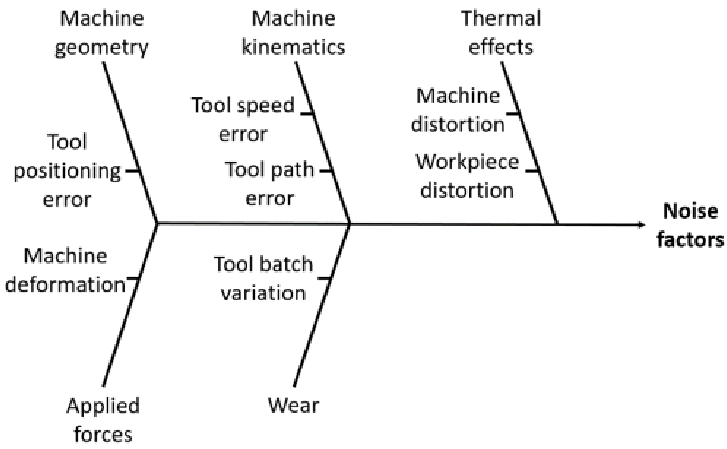

Figure 6: Ishikawa diagram showing noise factors in fabrication processes

In order to control the process and achieve the desired output, there are certain settings and parameters that can be used. In a non-adaptive manufacturing process, these settings are chosen during the design phase based on the expected values of all random factors that affect the process. In some cases, the settings are adjusted manually based on experience. These control factors are summarized in Figure 7.

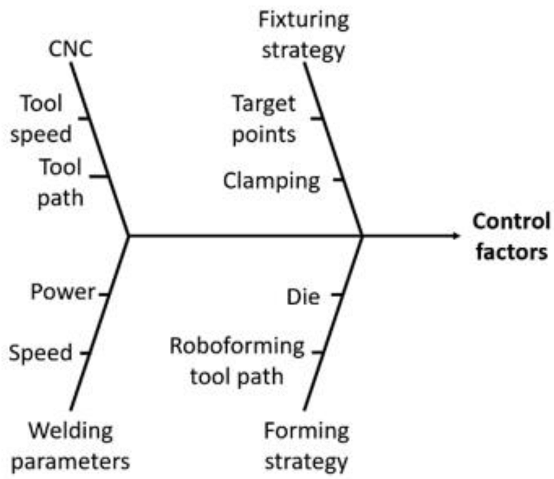

Figure 7: Ishikawa diagram showing control factors in fabrication processes

A manufacturing process usually consists of a series of individual operations where the workpiece undergoes certain alterations in order to create a finished product. Each operation makes changes to the geometry, the internal stress state, and the microstructure of the part. During each operation, some amount of random variation will be added to the product. This variation can be estimated with statistical methods, but the exact output of an operation is unknowable until it is measured and quantified. In every operation, the possibility of controlling certain settings and parameters creates an opportunity to compensate the variation that has occurred in previous steps of the manufacturing process. This requires that the variation can first be correctly measured. Variation that occurs early in the manufacturing process may propagate and cause problems in the final product. This can be avoided by measuring variation during the process and compensating it by adapting the subsequent operation as seen in the example in Figure 8. In this case, the geometry of the part is measured after the first operation and sent to a digital twin of the second operation. Due to random variation and noise that is always present to some extent, this geometry will have unique properties. Normally, all operations are calibrated based on the expected properties of the part. The measurement makes it possible to simulate how the second operation and its output will be influenced by this specific geometry, and whether the quality of the final product will be affected as a result. Provided that the simulated prediction is accurate, it is possible to select optimal settings for the second operation in order to get the best possible quality in the final product under current conditions. The goal is to create a proactive and adjustable manufacturing process that minimizes variation (Boorla, Eifler et al. 2018).

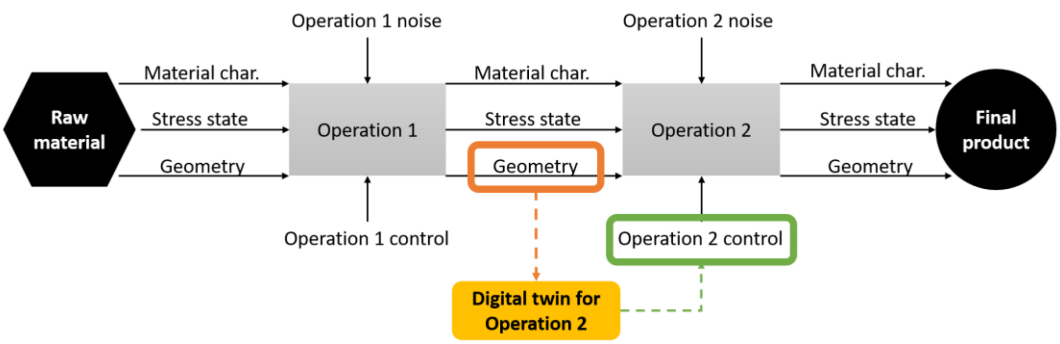

Figure 8: An example of a manufacturing process with two operations, showing how the digital twin can be implemented into the process to control the second operation based on measurements collected after the first operation

4.2 Result 2: Basic requirements of a digital twin for fabrication

The first result outlines the basic role of a digital twin in a manufacturing process, and shows that the digital twin needs to be able to: 1) collect data from an ongoing process through measurements, 2) analyze that data to predict how the measured variation will affect the final product, and 3) use this prediction in order to adjust and optimize the manufacturing process. For each of these three steps, there are several different approaches that can be taken, depending on the type of product and manufacturing process. In this case, focus lies on fabrication of aerospace components. The workflow for a digital twin in a fabrication process is outlined in Figure 9.

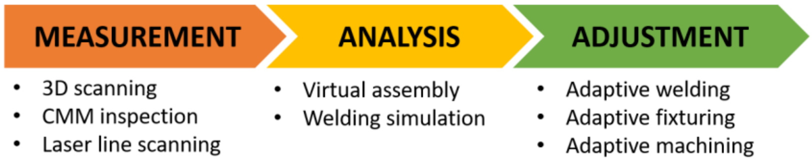

Figure 9: Workflow for digital twin in a fabrication process, based on the implementation shown in Figure 8

The first basic requirement for creating a digital twin is data collection. Since the digital twin is meant to mirror some aspect of a physical process, some measurements must be collected that quantify this chosen aspect or property. The types of data that are relevant to collect from the process can be deduced from the diagram in Figure 5. The work presented in this thesis focuses on geometrical properties. A measuring method that is becoming increasingly common within manufacturing is 3D scanning. This makes it possible to convert the surface of a part into a digital point cloud where each point corresponds to the measured surface (Schleich, Anwer et al. 2014). This is done by capturing beams that are reflected off the surface of the part. This method is capable of measuring a large surface in a short amount of time. Measurements may have reduced accuracy near sharp edges and corners since these often reflect light in unpredictable directions, and there will be blind spots on surfaces that do not have line of sight to the scanning device. An alternative method for measuring surfaces is CMM (Coordinate Measuring Machine) inspection. CMM uses a probe that is dragged along the surface of the part while the position of the probe is continuously measured. This results in a set of data points that describe the surface along the selected line. CMM is highly accurate and reliable. However, since it only measures a specific line on the surface, the inspection points must be selected carefully in order to maximize the usefulness of the data (Schleich, Wärmefjord et al. 2018). As an alternative to CMM, laser line scanning can be used to optically measure a line on the surface by reflecting light. This is quicker but less reliable than CMM, and can be useful in certain situations. Laser line scanning was used for weld seam alignment in (Tingelstad and Egeland 2014), and used in combination with CMM in (Boeckmans, Probst et al. 2016).

The second component required in a digital twin is data analysis. The goal of the analysis is to predict the output of a process based on the measured data. Most fabrication processes make extensive use of welding in in order to join parts together, and the scope of this work has therefore been limited to simulating how an assembly of parts react during a welding operation. Since this implementation should be based on measured geometrical data from parts, a regular nominal welding simulation cannot be used. First a virtual assembly must be created that mirrors the real parts that are going to be welded together on the assembly line. The welding process can then be mirrored by modeling the heat source to match the effect and movement of the real weld gun.

Finally, the digital twin has to feed the learnings from the predictive analysis back to the real process before it is initiated. Depending on the process, different options and settings will be available for adjustment in order to optimize the outcome (Söderberg, Wärmefjord et al. 2017). Once again, this work focuses on fabrication processes, which narrows the possibilities down to a few viable options for process adjustment. Adaptive locator adjustments have previously been proposed as a way of improving geometrical quality (Rezaei Aderiani, Wärmefjord et al. 2019), and has been shown to yield good experimental results for fabricated assemblies (Forslund, Lorin et al. 2018). Since machining is often involved in fabrication, this process can also be adjusted adaptively. Adaptive machining was proposed in (Li and Zhu 2019). Since the tool paths can be adjusted very precisely in order to make corrections to machined surfaces on a part, this can be used to adapt a part based on predictions made by a digital twin.

4.3 Result 3: Proposed internal functionality of a digital twin for a fabrication process

Based on the workflow that was outlined in Figure 9, an analysis loop is proposed for a digital twin for fabrication processes as shown in Figure 10. An iterative process is used where a different set of process parameters is used together with measured geometrical data in each loop until an acceptable outcome is predicted. The real process can then be initiated with these parameters.

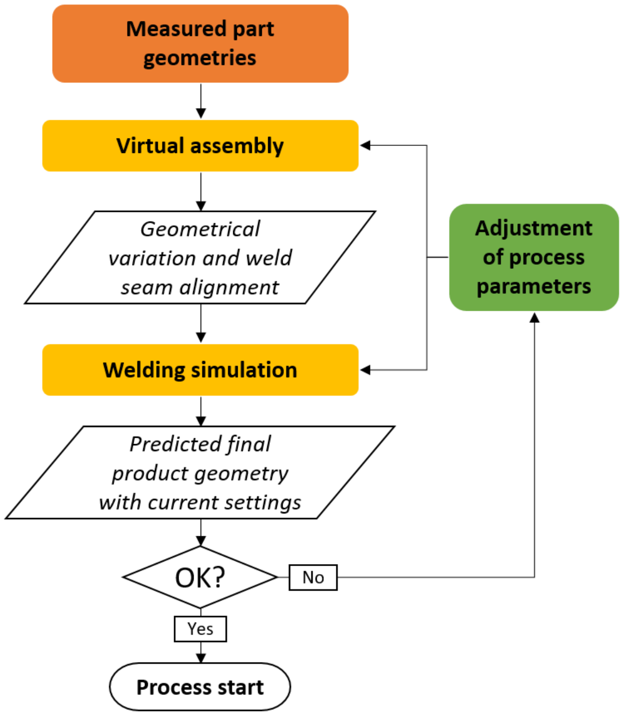

Figure 10: Proposed analysis loop for digital twin with virtual assembly and welding simulation

In this implementation, the geometrical data is collected through 3D scanning which generates a point cloud representing the surface of the part. The point cloud is positioned in the virtual environment by applying the relevant locating scheme and adjusting the locating points to their nominal positions. Since the goal is to perform a welding simulation, an FEM model with the same geometry as the real part is required. This model is generated by overlaying the point cloud on a nominal meshed CAD model for the part, and then warping the mesh by moving each node in the normal direction so that it matches the point cloud. The non-nominal meshed geometry is then placed in a virtual assembly that matches the real weld assembly, with the same weld seam alignment and geometrical variation in the interface between the parts. A welding simulation can now be performed on the virtual assembly by applying a heat source to the weld seam and calculating how the welded assembly will deform when as the material in the seam melts and then solidifies. Different welding methods can be used depending on time constraints and required accuracy. The simulation result is then checked and compared to the requirements on the final product. If the prediction shows that the measured part variation will lead to a final product that does not conform to its requirements, an adjustment is needed in the process to stop variation at the part level from propagating to the assembly level. Different process configurations can then be evaluated using the same analysis loop with different settings, until a configuration is found that can mitigate the geometrical variation and lead to a final product that complies to its requirements.

4.4 Result 4: Investigating the coupling effects between geometric variation and welding deformation in a digital twin

When running the analysis loop shown in Figure 10, the welding simulation is by far the most computationally heavy part of the loop. An alternative to this setup would be to run the welding simulation separately on a nominal assembly. The analysis loop would then consist of a virtual assembly followed by application of a pre-calculated welding deformation from a nominal welding simulation. This would be faster than running a non-nominal welding simulation in each loop. In order to investigate the feasibility of this alternative, a comparison was made between these two analysis methods. Three measuring points were chosen as shown in Figure 11. In each of these points, the deformation calculated from a nominal transient welding simulation is added to the deviation in that point measured from the part before welding. A second analysis is performed with a non-nominal transient welding simulation which directly incorporates the measured deviation into the simulation. The results for the three measuring points are shown in Table 3, Table 4, and Table 5 respectively. Any difference between the calculated deformations of the two approaches will indicate that the welding deformation is coupled to the geometrical variation in the parts. The difference is shown in the last column of each table, and a larger value indicates a higher degree of coupling between geometrical variation and welding deformation. These results show that since there is a coupling effect between geometric variation and welding deformation, it is necessary to run a non-nominal welding simulation in each iterative analysis loop as shown in Figure 10 in order to achieve the best possible accuracy. The simulation time becomes an important consideration since the analysis loop needs to be repeated several times in order to identify ideal process settings corresponding to the collected part measurement data.

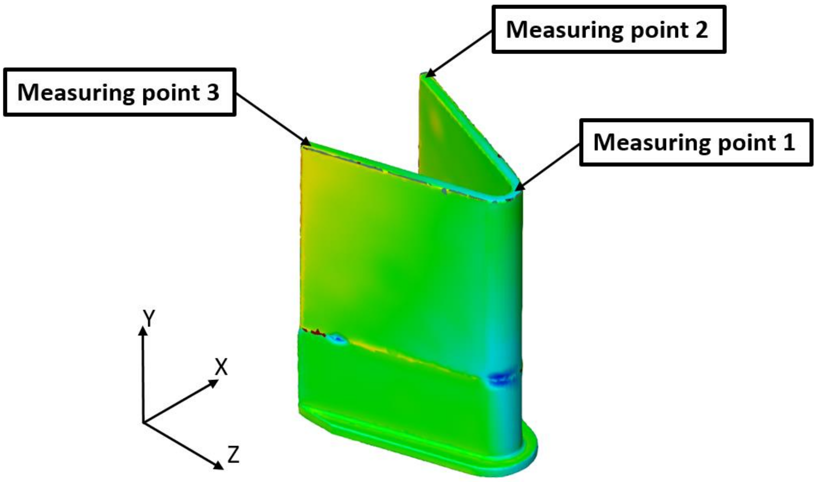

Figure 11: Locations of the three measuring points used for comparisons between nominal and non-nominal welding simulations

Table 3: Measuring point 1

Direction	Part nr.	Nominal weld simulation	Non-nominal weld simulation	Difference
X	1	0.01	0.03	0.02
	2	0.01	0.02	0.01
	3	0.01	0	-0.01
	4	0.01	0	-0.01
	5	0.01	0	-0.01
Y	1	-0.04	-0.06	-0.02
	2	-0.3	-0.08	0.22
	3	-0.28	-0.08	0.2
	4	-0.28	-0.08	0.2
	5	-0.27	-0.08	0.19
Z	1	0.03	0.02	-0.01
	2	0.03	0.04	0.01
	3	0.03	0.04	0.01
	4	0.03	0.04	0.01
	5	0.03	0.04	0.01

Table 4: Measuring point 2

Direction	Part nr.	Nominal weld simulation	Non-nominal weld simulation	Difference
X	1	0.01	0.06	0.05
	2	0.01	0.04	0.03
	3	0.01	-0.01	-0.02
	4	0.01	0	-0.01
	5	0.01	0	-0.01
Y	1	0.21	-0.03	-0.24
	2	0.08	-0.03	-0.11
	3	0.04	-0.03	-0.07
	4	0.05	-0.03	-0.08
	5	0.04	-0.03	-0.07
Z	1	0.02	0.03	0.01
	2	0.02	0.04	0.02
	3	0.02	0.03	0.01
	4	0.02	0.03	0.01
	5	0.02	0.03	0.01

Table 5: Measuring point 3

Direction	Part nr.	Nominal weld simulation	Non-nominal weld simulation	Difference
X	1	0	0.05	0.05
	2	0	0.03	0.03
	3	0	-0.01	-0.01
	4	0	0	0
	5	0	0	0
Y	1	0.14	-0.03	-0.17
	2	0.02	-0.03	-0.05
	3	0.04	-0.03	-0.07
	4	0.04	-0.03	-0.07
	5	0.04	-0.03	-0.07
Z	1	0.03	0	-0.03
	2	0.03	0.03	0
	3	0.03	0.04	0.01
	4	0.03	0.04	0.01
	5	0.03	0.04	0.01

4.5 Result 5: Evaluating the accuracy of the proposed digital twin

In order for the analysis loop in Figure 10 to work as intended, the predictive simulation component must be accurate enough to provide a useful decision basis for the adjustment of process parameters. The minimum requirement for the prediction is that it must be closer to the real welding outcome than a simulation based on nominal inputs. If this is not achieved, the digital twin will be pointless since it will not be able to improve on the predictions made during the design process. Simulation speed will also play an important role in the implementation of the analysis loop. The digital twin needs to provide a set of optimized process parameters before the scheduled start of the process, otherwise it will slow down the entire production line. The time it takes to complete one iteration of the analysis loop will determine the number of iterations that can be completed to evaluate different sets of process parameters. Faster simulation speed will allow more sets to be evaluated, leading to more optimized decisions over time.

To evaluate the feasibility of the proposed system, a test manufacturing process in a lab environment is used in combination with a digital twin that implements a non-nominal welding simulation. This setup makes it possible to directly compare the prediction of the non-nominal welding simulation to the actual output of the welding process. In this case study, the RD&T software (RD&T Technology 2023) is used to perform the analysis. The test manufacturing process is a simplified version of a full scale fabrication process for aerospace components. While the geometry is basic and consists of mostly flat surfaces and a single weld seam, the process incorporates the same types of manufacturing methods that are used in the industrial context. As seen in Figure 12, the assembly consists of two parts with a single weld seam that curves around the front of the part. The base (part 1) is made through machining while the top (part 2) is made through sheet metal forming. This combination is common in fabrication of aerospace engine components, and one of the main challenges is to take the welding deformation into account in order to achieve high geometric quality in the final product (Camuz, Lorin et al. 2019).

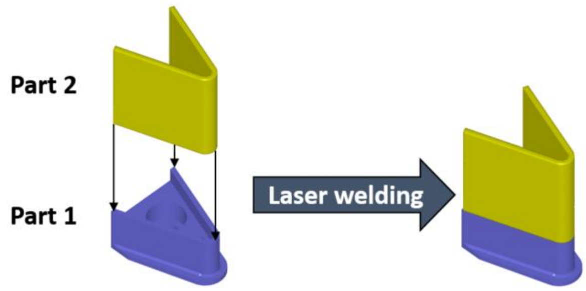

Figure 12: Weld assembly for the test manufacturing process

The goal of the digital twin in this case study is to predict the exact shape of the final welded component based on measurement data collected before the welding process is initiated. An accurate prediction is a prerequisite if the digital twin is to be used for optimizing the final product. In this case, geometrical data is collected from a 3D scan of part 2. Since sheet metal forming is less precise than machining, the geometrical variation will be concentrated to the sheet metal part of the assembly. The point cloud generated by the 3D scan is positioned based on locating points on the weld interface. The geometrical variation described by the point cloud is then transferred to a nominal meshed CAD model of part 2 that is warped in order to match the scan data from the real part. This non-nominal mesh can then be positioned on a mesh representing part 1, to create a virtual assembly with a weld interface that mirrors the conditions in the real weld assembly. A welding simulation with non-nominal geometrical data can then be performed on the virtual assembly to calculate the final geometry of the welded part. As shown in Figure 13, a 3D scan of the real welded component can then be directly compared to the simulation result in order to evaluate the accuracy of the digital twin.

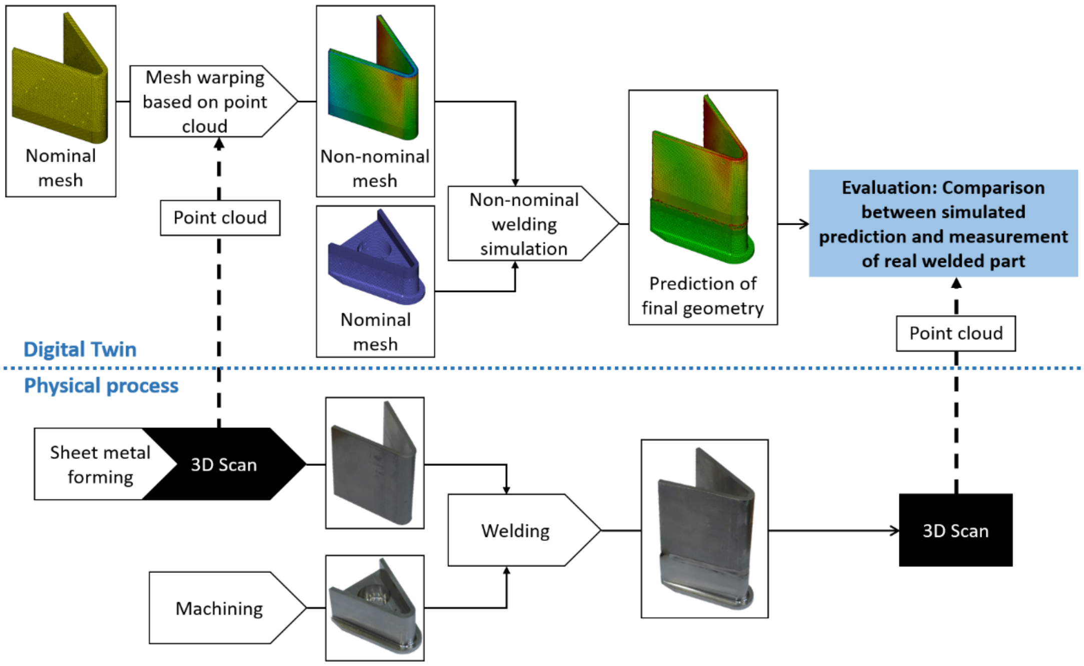

Figure 13: Overview of the case study and the interaction between the physical process and the digital twin

As previously mentioned, a balance between accuracy and speed are required from the welding simulation used in the digital twin. In this case study, three different types of welding simulation are used and evaluated. The first is a traditional transient welding simulation, similar to the type of simulation commonly used during the design phase when there are no time constraints. The heat is applied to the weld seam in small steps corresponding to half of the mesh element size followed by a calculation of the mechanical response. The second simulation is done with the SCV method, meaning that the melt zone is described with a single 2D profile which is applied to the entire weld seam on the 3D model (Lorin, Cromvik et al. 2014). A third and final simulation is done with the SCV method using a segmented weld seam where the 2D melt zone is calculated separately for the segments described in Figure 14, in order to increase the level of detail in the simulation.

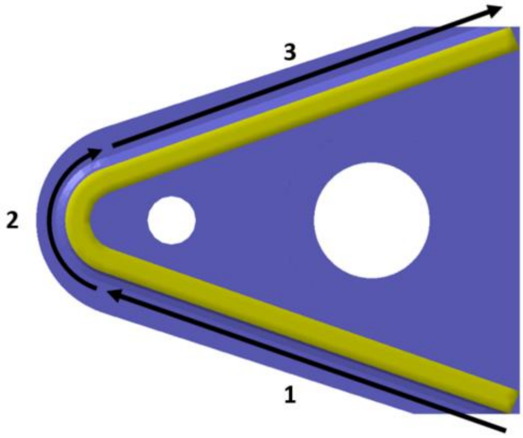

Figure 14: The weld seam is divided into three segments for the segmented SCV simulation

Mesh resolution is also evaluated. Each of the three weld simulation methods are evaluated with three different element sizes in the weld seam to draw conclusions on how accuracy and simulation time are affected. The mesh resolutions are shown in Figure 15. Only the element size close to the weld seam is changed between the three models, since there is no interest in changing the elements outside of the melted zone in this case.

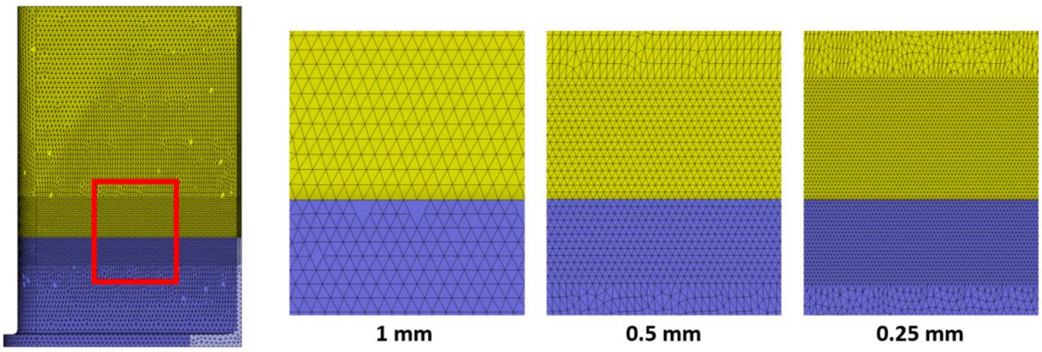

Figure 15: The three different mesh resolutions that are evaluated in welding simulations

The goal is to evaluate the result of the welding simulation by comparing it to scan data from the real welding result. In this study, five assemblies are scanned and welded to assess the accuracy of welding simulations based on the scan data. For each of the five assemblies and for each of the different simulation setups, an RMS (Root Mean Square) value is generated based on the distance between the surface of the simulated welded component and a set of measurement points from the surface of the real welded component. The top surface of the welded component is particularly sensitive to shrinkage from the welding, and in a larger assembly the geometrical variation on this surface would be transferred to an adjacent part. Therefore, only the measurement points on this surface are used to generate the RMS value. An example is shown in Figure 16, where a color plot is used to show the difference between the simulated weld result and real measurement points on different parts of the surface.

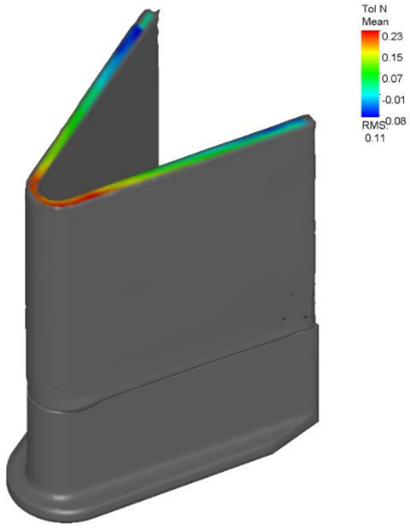

Figure 16: An example showing a visualization of the difference between the top surface of a simulated and real welded assembly

The results from the comparisons are shown in Table 6 and Table 7. Since the RMS values are based on the distance between the surface on a simulated model and the corresponding surface on the welded assembly that the simulation is trying to predict, a perfect simulation would produce an RMS value of zero. A lower value therefore indicates a more successful simulation, and RMS values for a straight comparison between the real welded assembly and a nominal model with no simulation is shown as a reference. Table 6 lists RMS values for each individual assembly, showing how the unique geometrical variation measured from different part has an effect on the accuracy of the welding simulation. In Table 7, average and median values are presented that indicate the overall accuracy of the different simulation methods. The lowest RMS values, corresponding to the most accurate simulation in each column, are underlined for clarity. The average simulation time is also shown in order to compare the computation speed of the simulation methods. These results indicate that the proposed non-nominal welding simulation method beats the accuracy of a traditional, nominal prediction without simulation. A comparison between different simulation setups show that the increased mesh resolution did not significantly improve the accuracy in this particular case, indicating that the model resolution had reached a point of convergence at 1 mm. The segmented SCV method yielded results that generally matched the accuracy of a full transient simulation, while being significantly faster.

Table 6: Results for the different simulation methods on five welded assemblies

Element size	Simulation method	RMS, Assy 1	RMS, Assy 2	RMS, Assy 3	RMS, Assy 4	RMS, Assy 5
-	No simulation	0,28	0,17	0,18	0,27	0,2
1mm	Regular SCV	0,11	0,1	0,09	<u>0,11</u>	0,05
	Segmented SCV	<u>0,09</u>	0,08	<u>0,07</u>	0,14	<u>0,03</u>
	Transient	0,1	0,09	0,09	0,14	<u>0,03</u>
0.5mm	Regular SCV	0,11	0,1	0,09	0,12	0,05
	Segmented SCV	<u>0,09</u>	0,08	<u>0,07</u>	0,13	<u>0,03</u>
	Transient	<u>0,09</u>	<u>0,07</u>	<u>0,07</u>	0,14	<u>0,03</u>
0.25mm	Regular SCV	0,11	0,1	0,09	0,12	0,05
	Segmented SCV	<u>0,09</u>	0,08	<u>0,07</u>	0,13	<u>0,03</u>
	Transient	<u>0,09</u>	0,08	0,08	0,14	<u>0,03</u>

Table 7: Average and median values based on results from the five welded assemblies

Element size	Simulation method	RMS, Average	RMS, Median	Average simulation time [minutes]
-	No simulation	0,22	0,2	-
1mm	Regular SCV	0,092	0,1	1,3
	Segmented SCV	0,082	0,08	1,3
	Transient	0,09	0,09	23,5
0.5mm	Regular SCV	0,094	0,1	3,0
	Segmented SCV	<u>0,08</u>	0,08	3,1
	Transient	<u>0,08</u>	<u>0,07</u>	79,1
0.25mm	Regular SCV	0,094	0,1	51,5
	Segmented SCV	<u>0,08</u>	0,08	46,0
	Transient	0,084	0,08	482,6

5 Discussion

5.1 Answering the research questions

RQ1: What affects the geometric quality in a fabrication process at the individual part level?

The first research question was approached by defining three categories of factors which affect the geometrical quality of fabricated components. These results were presented in Paper A. The first category is related to the properties of the workpiece going into the process, while the second and third categories focus on properties within the process itself as shown in Figure 4. The properties of the workpiece are shown in Figure 5. These properties can be observed and quantified by measuring the workpiece before the start of a process. During the process, some amount of random noise will be present which affects the output of the process. These noise factors are presented in Figure 6. Noise factors can be mitigated to some extent by manufacturing the product in a highly controlled environment, but no process is completely free from noise. The unique combination of the properties of the workpiece and the random noise in the process itself will result in an output which can never be fully predicted. However, it is still possible to fine-tune or adapt the process by making use of the settings and parameters which control the behavior of the process. These control factors are shown in Figure 7. Due to the random nature of a manufacturing process, there is always a unique configuration of settings for each process and each workpiece which will optimize the geometrical quality of the final product. While the random noise makes it impossible to exactly calculate this configuration, the process settings can be fine-tuned from their nominal values by taking the workpiece characteristics and process noise factors into account. This can be done by replacing nominal data and estimated conditions with up-to-date measurement data collected directly from the process. A process simulation can then be conducted in order to get a better estimation of how these measured conditions will affect the outcome.

Answering the first research question lays the foundation for the rest of the research project by clarifying the context of the digital twin for fabrication, making it possible to outline its design requirements.

RQ2: How can welding simulation be implemented to create a digital twin of a fabrication process?

Answering this research question requires multiple steps. First, the functionality of the digital twin itself must be defined in order to understand how the welding simulation module should be implemented. Once this digital twin framework is in place, a welding simulation method can be proposed which meets these requirements. Finally, the performance and accuracy of the proposed welding simulation method needs to be evaluated in this specific context. This work was performed across Paper A, B, and C.

Based on the context defined by answering the first research question, an analysis loop was proposed shown in Figure 10. In this implementation, the welding simulation is applied to a virtual assembly based on scan data from the real parts that are to be joined together. A welding process was set up in a lab environment in order to be able to collect data from physical parts. This scan data was imported into a welding simulation which was conducted in the RD&T software. The result of the simulation was then compared to the output of the real welding process in order to check its accuracy, as shown in Figure 13. Five assemblies were scanned, welded, and analyzed in order to account for variation between individual parts. Results show that the predictions generated by the proposed welding simulation is more accurate than the nominal assumptions that are currently being used in the manufacturing environment. Prediction errors for nominal and non-nominal methods are compared in Table 6 and Table 7. An answer can thereby be given to the second research question, showing how non-nominal welding simulation with scan data can be used in order to predict the behavior of welded assemblies on an individual basis.

RQ3: How can a digital twin improve the geometrical quality of a fabricated welded assembly to support individualized manufacturing?

Having defined a welding simulation implementation suited for a digital twin, the next step is to use the prediction generated by the simulation in order to adjust the welding process proactively and achieve a more optimized result based on the unique conditions of each individual assembly. Since the research project is not yet complete, the third research question can only be partially answered through the results presented in this thesis. The analysis loop shown in Figure 10 needs to be completed by implementing an adaptive adjustment, which can then be evaluated in a lab environment. This will finalize the support that this research aims to propose for industrial implementation in high precision fabrication processes.

5.2 Assessing the quality of the research

There are four requirements that can be said to be particularly relevant for the trustworthiness and quality of research within the field of operations management (Karlsson 2016). These requirements are construct validity, internal validity, external validity, and reliability. In this case, validity is related to *doing the right things*, and reliability is related to *doing things right*. In other words, the four main requirements are a way of ensuring that the researcher has selected an appropriate method for the research project, and that this chosen method has been executed in a rigid and correct manner.

Construct validity questions whether the research is truly investigating the construct that it claims to be investigating. Most research projects involve some type of construct, a concept that is important within the research field but which cannot be measured directly and therefore has to be judged or inferred from observable and quantifiable data. Making sure that this inference is clear and sound is foundational to the value of the research. In this research project, a central construct is the concept of geometrical quality. The aim of the proposed digital twin is to increase the geometrical quality of fabricated components by studying measurement data from a welded assembly in a lab environment. The link between this measurement data and the generalized concept of geometrical quality is based on experiential knowledge from fabrication of aerospace engine components. This link is strengthened through the results presented in Paper A, answering the first research question about how variation at the individual part level affects the geometrical quality at the assembly level and in the final product.

Internal validity is related to whether there is causality between the proposed support and the variable that is being studied. In this thesis, it is hypothesized that the use of a non-nominal welding simulation will improve the predictive accuracy for a welded assembly compared to a nominal welding simulation. In order to strengthen the internal validity of the study, multiple welded assemblies were studied to reduce the influence of random noise in the welding or measurement process. The case study is based on an assembly with a single weld seam, and the geometry of the parts are simplified with mostly flat surfaces and straight edges. This simplification creates a more controlled environment with fewer unknown phenomena related to the complex dynamics of heat transfer and welding deformation.

External validity concerns the applicability of the research results to a broader, more generalized context. As previously mentioned, the case study was based on a simplified version of the intended environment of the proposed digital twin. The geometry of the parts is less complex and there are fewer weld seams compared to the type of product that is based on. While the simplification creates a more controlled environment with fewer unknown factors, it also results in a setting which is less similar to a real fabrication process. However, the variation sources identified in Paper A and the predictive functionality of the digital twin proposed in Paper B are replicated in the case study which supports the generalizability of the results.

Reliability focuses on the execution of the case study, rather than its conceptual design. In (Yin 2009), it is proposed that the reliability of a case study can be increased by documenting the procedures of the study rigorously. Carefully checking the codes and transcripts used in the study have also been held forward as important factors when it comes to reliability (Fetters, Curry et al. 2013). The procedures applied during the case study have been detailed in this thesis in order to enable replication of the presented results. During the case study, these procedures were followed closely and double checked carefully to reduce the risk of inconsistencies in the execution of the study.

5.3 Research contribution

The results presented in this thesis make contributions within both an industrial and an academic context. The academic contribution mainly consists in a continuation of the research work which has previously been done within the fields of geometry assurance, welding simulation, and digital twins for manufacturing. By combining aspects of these fields, new knowledge and insight is created. While previous research within geometry assurance has mainly focused on statistical methods applied in the design phase, the results in this thesis show how geometry assurance can be applied on an individual basis in the production phase by making use of data collection and simulation. Non-nominal welding simulation has previously been demonstrated in a virtual environment with random variation, a method which is here continued and expanded by using variation measured from a physical environment in order to further evaluate the non-nominal simulation approach. Previous work on digital twins for manufacturing has mainly focused on proposing a theoretical framework for the basic role of a digital twin in a production environment. The results presented here show how a digital twin can be implemented in the specific case of a fabrication process, where the capability of the digital twin is uniquely useful for improving the geometrical quality by individualizing the process.

In the industrial context, the main contribution of this thesis is the successful demonstration of the capability of a digital twin. The main goal of any work within the field of operations research is ultimately to implement a support that improves some aspect of an operation. Besides conceptualizing and developing the support, but it is also important to demonstrate that it is able to reduce costs in order to incentivize and drive implementation. If this cannot be done, the development of the support will remain as a purely academic exercise. By setting up a test manufacturing process in a lab environment which recreates some of the challenges of a real fabrication process, the work presented in this thesis demonstrates the predictive capabilities of a digital twin in this context. The results show that the digital twin is able to receive measurement data from the process and use it to generate a prediction of its behavior which is more accurate than a nominal prediction. This represents an important milestone on the road towards demonstrating a finalized digital twin which is able to both receive data and feed information back to the production process.

6 Conclusion

Increasing demands on weight and efficiency are pushing the aerospace industry towards innovative manufacturing methods. One such method is fabrication, which enables new design solutions and lowered weight while also increasing the amount of geometrical variation in the manufacturing process. In order to manage this geometrical variation and ensure that the final product meets its requirements, digital twins have been proposed as a way of controlling the process. Digital twins make use of measurement data and process simulation to create a virtual copy of the physical process. In this thesis, an implementation is proposed that applies the digital twin concept to a process where a machined part and a sheet metal are joined with welding. An analysis loop is developed that includes virtual assembly and welding simulation based on scan data from the parts, with the goal of predicting the outcome of the welding process based on the unique geometrical variation in each set of parts. A case study is set up with test manufacturing in a lab environment, where the prediction accuracy of the proposed digital twin can be evaluated by comparing the simulation result to scan data from the real welded assembly. Comparisons show that the digital twin outperforms a nominal prediction of the welding process output, indicating that it is capable of predicting individual behaviors and phenomena in the welding process based on scan data from each set of parts. Results from the case study also show that the welding deformation and the geometrical variation in the parts are coupled, meaning that the welding simulation must be performed using a non-nominal assembly in order to achieve the best possible accuracy.

Future work will continue to contribute towards the main goal of achieving an individualized fabrication process with the help of the proposed digital twin. The next step is to implement and evaluate an adaptive adjustment to the welding process based on the prediction from the digital twin. This would prove that it is possible to individualize the fabrication process in the case study by sending scan data to a digital twin and then feeding back a recommended adjustment to the process, achieving two-way communication between the digital twin and the physical process. A possible approach is to use adaptive machining in order to adjust the interfaces of a machined part in order to mitigate geometrical variation in measured sheet metal parts. This should first be proven in a simple two part assembly, before moving on to a more realistic and complex assembly with multiple parts and interfaces where geometrical variation can affect the quality of the final product. In the long term, efforts should also be made to collect more data from the parts in order to make the digital twin capable of more detailed predictions and more fine-tuned adaptive process adjustments.

7 References

Bachorski, A., M. Painter, A. Smailes and M. A. Wahab (1999). "Finite-element prediction of distortion during gas metal arc welding using the shrinkage volume approach." Journal of materials processing technology **92**: 405-409.
Blessing, L. T. and A. Chakrabarti (2009). DRM: A design reseach methodology, Springer.
Boeckmans, B., G. Probst, M. Zhang, W. Dewulf and J.-P. Kruth (2016). ISO 10360 verification tests applied to CMMs equipped with a laser line scanner. Dimensional Optical Metrology and Inspection for Practical Applications V, International Society for Optics and Photonics.
Boorla, M. S., T. Eifler, C. McMahon and T. J. Howard (2018). "Product robustness philosophy–A strategy towards zero variation manufacturing (ZVM)." Management and Production Engineering Review **9**(2): 3-12.
Cai, W., S. J. Hu and J. Yuan (1996). "Deformable sheet metal fixturing: principles, algorithms, and simulations."
Camilleri, D., T. Comlekci and T. G. Gray (2006). "Thermal distortion of stiffened plate due to fillet welds computational and experimental investigation." Journal of Thermal Stresses **29**(2): 111-137.
Camuz, S., S. Lorin, K. Wärmefjord and R. Söderberg (2019). "Nonlinear material model in part variation simulations of sheet metals." Journal of Computing and Information Science in Engineering **19**(2).
Chase, K. W. and A. R. Parkinson (1991). "A survey of research in the application of tolerance analysis to the design of mechanical assemblies." Research in Engineering design **3**(1): 23-37.
Dahlström, S. and L. Lindkvist (2007). "Variation simulation of sheet metal assemblies using the method of influence coefficients with contact modeling."
Dong, P., S. Song and J. Zhang (2014). "Analysis of residual stress relief mechanisms in post-weld heat treatment." International Journal of Pressure Vessels and Piping **122**: 6-14.
Evans, D. H. (1975). "Statistical Tolerancing: The State of the Art: Part II. Methods for Estimating Moments." journal of quality technology **7**(1): 1-12.
Fetters, M. D., L. A. Curry and J. W. Creswell (2013). "Achieving integration in mixed methods designs—principles and practices." Health services research **48**(6pt2): 2134-2156.
Forslund, A. (2016). Uncertainty and robustness in aerospace structures, Chalmers University of Technology.
Forslund, A., S. Lorin, L. Lindkvist, K. Wärmefjord and R. Söderberg (2018). "Minimizing Weld Variation Effects Using Permutation Genetic Algorithms and Virtual Locator Trimming." Journal of Computing and Information Science in Engineering **18**(4): 041010-041010-041018.
Forslund, A., R. Söderberg and J. Lööf (2011). Multidisciplinary robustness evaluations of aero engine structures. 20th ISABE Conference 2011 Proceedings.

Gao, J., K. W. Chase and S. P. Magleby (1998). "Generalized 3-D tolerance analysis of mechanical assemblies with small kinematic adjustments." IIE transactions **30**(4): 367-377.

Glaessgen, E. H. and D. S. Stargel (2012). The digital twin paradigm for future NASA and U.S. Air force vehicles. Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference.

Goldak, J. A. and M. Akhlaghi (2005). Computational welding mechanics, Springer Science & Business Media.

Hong, Y. and T.-C. Chang (2002). "Tolerancing algebra: A building block for handling tolerance interactions in design and manufacturing part 1: Concept and representation." International journal of production research **40**(18): 4633-4649.

Karlsson, C. (2016). Research methods for operations management, Routledge London.

Kritzinger, W., M. Karner, G. Traar, J. Henjes and W. Sihn (2018). "Digital Twin in manufacturing: A categorical literature review and classification." IFAC-PapersOnLine **51**(11): 1016-1022.

Li, Z.-L. and L.-M. Zhu (2019). "Compensation of deformation errors in five-axis flank milling of thin-walled parts via tool path optimization." Precision Engineering **55**: 77-87.

Lindgren, L.-E. (2002). Modelling for residual stresses and deformations due to welding : "knowing what isn't necessary to know". International Seminar on Numerical Analysis of Weldability : 01/10/2001 - 02/10/2001. H. Cerjak and H. K. D. H. Bhadeshia. London, Maney Publishing (for The Institute of Materials, Minerals and Mining)**:** 491-518.

Liu, S. C. and S. J. Hu (1997). "Variation simulation for deformable sheet metal assemblies using finite element methods."

Lorin, S., C. Cromvik, F. Edelvik, L. Lindkvist and R. Söderberg (2014). On the robustness of the volumetric shrinkage method in the context of variation simulation. ASME International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers.

Lorin, S., C. Cromvik, F. Edelvik, L. Lindkvist and R. Söderberg (2014). "Variation Simulation of Welded Assemblies Using a Thermo-Elastic Finite Element Model." Journal of Computing and Information Science in Engineering **14**(3).

Lorin, S., C. Cromvik, F. Edelvik, L. Lindkvist, R. Söderberg and K. Wärmefjord (2014). Simulation of non-nominal welds by resolving the melted zone and its implication to variation simulation. ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection.

Lorin, S., C. Cromvik, F. Edelvik and R. Söderberg (2015). "Welding simulation of non-nominal structures with clamps." Journal of Computing and Information Science in Engineering **15**(2).

Lööf, J. (2010). Managing geometrical variation through optimization and visualization, Chalmers University of Technology.

Lööf, J., T. Hermansson and R. Söderberg (2007). An efficient solution to the discrete least-cost tolerance allocation problem with general loss functions. Models for computer aided tolerancing in design and manufacturing, Springer**:** 115-124.

Madrid, J. (2020). Design for Producibility in Fabricated Aerospace Components-A framework for predicting and controlling geometrical variation and weld quality defects during multidisciplinary design, Chalmers Tekniska Hogskola (Sweden).

Madrid, J., S. Lorin, R. Söderberg, P. Hammersberg, K. Wärmefjord and J. Lööf (2019). "A virtual design of experiments method to evaluate the effect of design and welding parameters on weld quality in aerospace applications." Aerospace **6**(6): 74.

Madrid, J., R. Söderberg, J. Vallhagen and K. Wärmefjord (2016). "Development of a Conceptual Framework to Assess Producibility for Fabricated Aerospace Components." Procedia CIRP **41**: 681-686.

Morse, E., J.-Y. Dantan, N. Anwer, R. Söderberg, G. Moroni, A. Qureshi, X. Jiang and L. Mathieu (2018). "Tolerancing: Managing uncertainty from conceptual design to final product." CIRP Annals **67**(2): 695-717.

Nigam, S. D. and J. U. Turner (1995). "Review of statistical approaches to tolerance analysis." Computer-Aided Design **27**(1): 6-15.

Phadke, M. S. (1995). Quality engineering using robust design, Prentice Hall PTR.

Ramesh, R., M. Mannan and A. Poo (2000). "Error compensation in machine tools—a review: Part II: thermal errors." International Journal of Machine Tools and Manufacture **40**(9): 1257-1284.

RD&T Technology (2023). RD&T Software Manual. R&DT Technology AB. Mölndal, Sweden. www.rdnt.se. [Accessed 2023-03-20].

Rezaei Aderiani, A., K. Wärmefjord, R. Söderberg and L. Lindkvist (2019). "Individualizing locator adjustments of assembly fixtures using a digital twin." Journal of Computing and Information Science in Engineering **19**(4).

Roy, R. B., D. Mishra, S. K. Pal, T. Chakravarty, S. Panda, M. G. Chandra, A. Pal, P. Misra, D. Chakravarty and S. Misra (2020). "Digital twin: current scenario and a case study on a manufacturing process." The International Journal of Advanced Manufacturing Technology **107**(9): 3691-3714.

Runnemalm, H., H. Tersing and O. Isaksson (2009). Virtual manufacturing of light weight aero engine components. International Symposium on Air Breathing Engines : 07/09/2009 - 11/09/2009.

Sagar, V. R., K. Wärmefjord and R. Söderberg (2019). "Influence of Selective Laser Heat Treatment Pattern Position on Geometrical Variation." Journal of Manufacturing Science and Engineering **141**(4): 041016.

Schleich, B., N. Anwer, L. Mathieu and S. Wartzack (2014). "Skin model shapes: A new paradigm shift for geometric variations modelling in mechanical engineering." Computer-Aided Design **50**: 1-15.

Schleich, B., N. Anwer, L. Mathieu and S. Wartzack (2017). "Shaping the digital twin for design and production engineering." CIRP Annals **66**(1): 141-144.

Schleich, B., M.-A. Dittrich, T. Clausmeyer, R. Damgrave, J. A. Erkoyuncu, B. Haefner, J. de Lange, D. Plakhotnik, W. Scheidel and T. Wuest (2019). "Shifting value stream patterns along the product lifecycle with digital twins." Procedia CIRP **86**: 3-11.

Schleich, B., K. Wärmefjord, R. Söderberg and S. Wartzack (2018). "Geometrical variations management 4.0: towards next generation geometry assurance." Procedia CIRP **75**: 3-10.

Shah, J. J., G. Ameta, Z. Shen and J. Davidson (2007). "Navigating the tolerance analysis maze." Computer-Aided Design and Applications **4**(5): 705-718.

Soderberg, R. and L. Lindkvist (1999). "Computer aided assembly robustness evaluation." Journal of Engineering Design **10**(2): 165-181.

Steffenburg-Nordenström, J. and M. Larsson (2014). Simulation of the influence of forming on residual stresses and deformations after welding and heat treatment in alloy 718. 11th World Congress on Computational Mechanics, WCCM 2014, 5th European Conference on Computational Mechanics, ECCM 2014 and 6th European Conference on Computational Fluid Dynamics, ECFD 2014.

Stylidis, K., C. Wickman and R. Söderberg (2020). "Perceived quality of products: a framework and attributes ranking method." Journal of Engineering Design **31**(1): 37-67.

Sulaiman, M. S., Y. H. Manurung, E. Haruman, M. R. A. Rahim, M. R. Redza, R. N. A. Lidam, S. K. Abas, G. Tham and C. Y. Chau (2011). "Simulation and experimental study on distortion of butt and T-joints using WELD PLANNER." Journal of Mechanical Science and Technology **25**(10): 2641-2646.

Söderberg, R. (1993). Tolerance allocation considering customer and manufacturer objectives. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.

Söderberg, R. (1994). Robust design by tolerance allocation considering quality and manufacturing cost. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.

Söderberg, R. (1995). Optimal tolerance band and manufacturing target for monotonic loss functions with functional limits. International Design

Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
Söderberg, R. and J. S. Carlson (1999). Locating scheme analysis for robust assembly and fixture design. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
Söderberg, R., L. Lindkvist and J. Carlson (2002). "Virtual geometry assurance for effective product realization."
Söderberg, R., L. Lindkvist and J. Carlson (2006). Virtual geometry assurance for effective product realization. 1st Nordic Conference on Product Lifecycle Management-NordPLM.
Söderberg, R., L. Lindkvist and J. S. Carlson (2006). "Managing physical dependencies through location system design." Journal of Engineering Design **17**(4): 325-346.
Söderberg, R., L. Lindkvist and S. Dahlström (2006). "Computer-aided robustness analysis for compliant assemblies." Journal of Engineering Design **17**(5): 411-428.
Söderberg, R., L. Lindkvist, K. Wärmefjord and J. S. Carlson (2016). "Virtual geometry assurance process and toolbox." Procedia Cirp **43**: 3-12.
Söderberg, R., K. Wärmefjord, J. S. Carlson and L. Lindkvist (2017). "Toward a Digital Twin for real-time geometry assurance in individualized production." CIRP Annals **66**(1): 137-140.
Söderberg, R., K. Wärmefjord, J. Madrid, S. Lorin, A. Forslund and L. Lindkvist (2018). "An information and simulation framework for increased quality in welded components." CIRP Annals **67**(1): 165-168.
Taguchi, G., S. Chowdhury and Y. Wu (2004). Taguchi's quality engineering handbook, John Wiley & Sons.
Taguchi, G. and Y.-I. Wu (1980). "Introduction to off-line quality control Systems." Central Japan QCA, Nagoyo.
Tao, F., H. Zhang, A. Liu and A. Y. Nee (2018). "Digital twin in industry: State-of-the-art." IEEE Transactions on industrial informatics **15**(4): 2405-2415.
Tingelstad, L. and O. Egeland (2014). "Robotic assembly of aircraft engine components using a closed-loop alignment process." Procedia CIRP **23**: 110-115.
Ueda, Y. and M. G. Yuan (1993). "A Predicting Method of Welding Residual Stress Using Source of Residual Stress (Report III): Prediction of Residual Stresses in T-and I-joints Using Inherent Strains (Mechanics, Strength & Structural Design)." Transactions of JWRI **22**(1): 157-168.
Vallhagen, J., O. Isaksson, R. Söderberg and K. Wärmefjord (2013). "A framework for producibility and design for manufacturing requirements in a system engineering context." Procedia CIRP **11**: 145-150.
Vallhagen, J., J. Lööf, R. Söderberg and K. Wärmefjord (2011). Robustness in aerospace components manufacturing and fabrication–a case study. Proceedings of ISABE2011.

Vallhagen, J., J. Madrid, R. Söderberg and K. Wärmefjord (2013). "An approach for producibility and DFM-methodology in aerospace engine component development." Procedia CIRP **11**: 151-156.
Wolff, S. (2014). Robustness evaluation in sheet metal forming using statistics on structures (SoS) and optiSLang. Proceedings 32nd German ANSYS and CADFEM Users' Meeting, Nürnberg, Germany.
Wärmefjord, K., L. Lindkvist and R. Söderberg (2008). Tolerance Simulation of Compliant Sheet Metal Assemblies Using Automatic Node-Based Contact Detection. ASME 2008 International Mechanical Engineering Congress and Exposition.
Wärmefjord, K., R. Söderberg, B. Lindau, L. Lindkvist and S. Lorin (2016). "Joining in nonrigid variation simulation." Computer-aided Technologies–Applications in Engineering and Medicine.
Wärmefjord, K., R. Söderberg, L. Lindkvist, B. Lindau and J. S. Carlson (2017). Inspection data to support a digital twin for geometry assurance. ASME 2017 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers Digital Collection.
Yin, R. K. (2009). Case study research: Design and methods, sage.
Zhang, L., H. Wang and S. Li (2014). "Simulating Assembly Geometric and Stress Variation Considering Machining-Induced Residual Stress." (46353): V004T006A011.
Zhou, G., C. Zhang, Z. Li, K. Ding and C. Wang (2020). "Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing." International Journal of Production Research **58**(4): 1034-1051.