THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

JOINING SEQUENCE OPTIMIZATION IN COMPLIANT VARIATION SIMULATION

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Cover: Assembly geometrical deviation for different joining sequences in one of the test assemblies, see Papers 3-5

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Abstract

Disturbances in the manufacturing and assembly processes cause deviation and geometrical variation from the ideal geometry. This variation eventually results in functional and aesthetic problems in the final product. Being able to control the disturbances is the desire of the manufacturing industry. This, in other words, means turning the noise factors to control factors, in a robust design perspective.

With the recent breakthroughs in the technology, the new digitalization reform, and availability of big data from the manufacturing processes, the concepts of digital twins have grasped the attention of the researchers and the practitioners.

In line with this trend, Söderberg et al. have introduced the geometry assurance digital twin and the concept of the self-compensating individualized assembly line. Steering the assembly process with online real-time optimization, through the digital twin medium is the vision of such a concept.

Joining sequences impact the final geometrical outcome in an assembly considerably. To optimize the sequence for the optimal geometrical outcome is both experimentally and computationally expensive. In the simulation-based approaches, several sequences need to be evaluated together with the finite element method and Monte Carlo simulations.

In this thesis, the simulation-based joining sequence optimization, using compliant variation simulation is studied. Initially, the limitations of the formulations and the applied algorithms in the literature have been addressed. Two evolutionary algorithms have been introduced to compare the computational performances to the genetic algorithm. Secondly, a reduced formulation of the sequence optimization is introduced through the identification of the critical points to lock the geometry, geometry joints. A rule-based method has been proposed to initiate the evolutionary algorithm and thereby to increase the algorithm's computational efficiency. This approach has been further improved by a contact displacement minimization approach to generate model-dependent rules. Finally, a surrogate-assisted approach has been introduced to parallelize the computation process, saving computation time drastically. The approach also unveiled the potential of the simulation-based geometry joint identification, simultaneous to complete sequence determination.

The results achieved from the presented studies indicate that the simulation-based real-time optimization of the joining sequences is achievable through a parallelized search algorithm, to be implemented in the geometry assurance digital twin concept. The results can help to control the joining sequence in the assembly process, improving the geometrical quality in a cost-effective manner, and saving significant computational time.

Keywords: Joining, Sequencing, Optimization, Compliant Variation Simulation.

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ROHAM SADEGHI TABAR
Gothenburg, September 2019

List of Publications

This thesis is based on the following appended papers:

Paper 1. Roham Sadeghi Tabar, Kristina Wärmefjord, Rikard Söderberg, 2018, *Evaluating evolutionary algorithms on spot welding sequence optimization with respect to geometrical variation.* Procedia CIRP, 75, pp. 421-426.

Paper 2. Roham Sadeghi Tabar, Kristina Wärmefjord, Rikard Söderberg, 2019, *A method for identification and sequence optimisation of geometry spot welds in a digital twin context.* Journal of Mechanical Engineering Science, Proceedings of the Institution of Mechanical Engineers Part C, 233 (16), pp. 5610-5621.

Paper 3. Roham Sadeghi Tabar, Kristina Wärmefjord, Rikard Söderberg, Lars Lindkvist 2019, *A Novel Rule-Based Method For Individualized Spot Welding Sequence Optimization With Respect to Geometrical Quality.* Journal of Manufacturing Science and Engineering, Accepted.

Paper 4. Roham Sadeghi Tabar, Kristina Wärmefjord, Rikard Söderberg, Lars Lindkvist 2019, *Efficient Spot Welding Sequence Optimization in a Geometry Assurance Digital Twin.* Journal of Mechanical Design, Submitted.

Paper 5. Roham Sadeghi Tabar, Kristina Wärmefjord, Rikard Söderberg, 2019, *A new surrogate model based method for individualized spot welding sequence optimization with respect to geometrical quality.* The International Journal of Advanced Manufacturing Technology, Submitted.

Distribution of Work

The distribution of the work for each paper is as follows:

Paper 1. Sadeghi Tabar, Wärmefjord, and Söderberg initiated the idea. Sadeghi Tabar carried out the studies and wrote the paper, with Wärmefjord and Söderberg acting as reviewers.

Paper 2. Sadeghi Tabar initiated the idea and carried out the studies with some guidance from Wärmefjord. Sadeghi Tabar wrote the paper, with Wärmefjord and Söderberg acting as reviewers.

Paper 3. Sadeghi Tabar initiated the idea and carried out the studies with some guidance from Wärmefjord. Lindkvist supported building the interface between the simulation software and the optimization algorithm. Sadeghi Tabar wrote the paper, with Wärmefjord and Söderberg acting as reviewers.

Paper 4. Sadeghi Tabar initiated the idea and carried out the studies. Lindkvist supported the study with the simulation software. Sadeghi Tabar wrote the paper, with Wärmefjord, Söderberg, and Lindkvist acting as reviewers.

Paper 5. Sadeghi Tabar initiated the idea and carried out the studies. Sadeghi Tabar wrote the paper, with Wärmefjord and Söderberg acting as reviewers.

List of Acronyms

ACO – Ant Colony Optimization
CAT – Computer-Aided Tolerancing
CMM – Coordinate Measurement Machine
DoF – Degrees of Freedom
DMC – Direct Monte Carlo
DRM – Design Research Methodology
DS – Descriptive Study
GD&T – Geometrical Dimensioning and Tolerancing
FEA – Finite Element Analysis
FEM – Finite Element Method
GA – Genetic Algorithm
MCD – Minimized Contact Displacements
MIC – Method of Influence Coefficients
MLS – Master Location System
NFE – Number of Function Evaluations
NN – Neural Network
NP – Non-deterministic Polynomial-time
PS – Prescriptive Study
PSO – Particle Swarm Optimization
RBGA – Rule-Based Genetic Algorithm
RC – Research Clarification
RMS – Root Mean Square
RQ – Research Question
RSS – Root Sum Square
RSW – Resistant Spot Welding
RD&T – Robust Design and Tolerancing
TSP – Traveling Salesman Problem

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II Appended Papers

Part I

Introductory Chapters

Chapter 1

INTRODUCTION

In the following, the introduction to the research is provided, and the scope of the presented study is defined.

1.1 Background

From the early existence of the humankind, product development has been an element of existence, from understanding a need to the realization of a product. Concept, verification, and production are the fundamental phases of the product realization cycle. Manufacturing processes are referred to as the steps through which raw materials are transformed into a final product. Thereby, manufacturing processes often take part in the transition between the concept and verification phases until the very end of production. Just like any aspect of the product development cycle, the manufacturing processes have been advanced to achieve products that are more effective and efficient. A logical requirement of such a process is that the manufactured product complies with the intended design. This requirement demands a manufacturing process with the capability of producing nominal products. However, with the industrial revolution and higher production rates, more products were needed to be delivered in shorter times. Therefore, the technological capability and the cost were delimiting manufacturing of products close to the nominal design. Eventually, mass production and customization resulted in products of several components to be assembled. Ever since, the assembly process has been an inevitable part of the manufacturing processes, until the product reaches the hands of the end-user.

Part variation together with the assembly variation, from processes such as fixturing and joining, result in the variation in the final products. Geometric dimensioning and tolerancing (GD&T) and the quality control methods, i.e., Taguchi and six-sigma, are developed to secure the geometrical outcome of the produced assemblies. Nevertheless, assignment of tighter tolerance requirements on the individual products increases the cost the product exponentially. The decision on the tolerance to be assigned, without the prior knowledge of the outcome of the assembly, is challenging. Therefore, the virtual tools, known as Computer-Aided Tolerancing (CAT), have been developed supporting the decision making during the product specification development, allowing the numerical simulation of the geometrical variation of the assemblies. These tools, not only made for the sole purpose of the early fault detection, but also to reach the lower cost production, and to achieve the environmental sustainability demands of the future manufacturing.

To assemble single components of a product, joining operations are required. Among other acting assembly parameters, the joining parameters affect the final geometrical outcome.

Today, in a highly automated production set-up, for complex assembled products, there could be up to several hundreds of robots organized into lines and stations for handling and joining operations. Therefore, the factory is a huge investment, and return on investment requires high product quality, factory throughput, equipment utilization, and flexibility as well as low energy consumption. Geometry related problems, resulting in late changes and delays, usually constitute a significant part of the total cost for poor quality. Previous research and industrial implementation have shown how CAT-tools and geometrical variation simulation improve quality, throughput, and energy consumption.

In this thesis, compliant, interchangeably non-rigid, assemblies are studied. In these assemblies, parts are bent and deformed during the assembly. Thereby, predicting the outcome of the assembly is more challenging. Numerical simulation methods, using finite element method (FEM) have been developed allowing this prediction, with the trade-off of the calculation time. The more complex the assembly, the longer the calculation time to simulate the geometrical outcome. Assembly complexity is defined as the size of the parts to be assembled, the mating conditions between the adjacent parts, and the requirements that need to be satisfied.
For compliant assemblies, the complexity of the assembly, as defined above, determines the joining parameters affecting the geometrical outcome, namely the number of the joints, their position, and also the sequence of joining. Joining sequences have shown to have a significant effect on the final geometrical outcome. The joining sequence effect the mechanistic behavior of the parts during the assembly, independent of the joint type. Spot welds and rivets and clip fasteners are among the dominating joint types in the non-rigid assemblies. Choosing the right joining sequence can help to reduce the geometrical deviation in the assembly. However, the choice of the right sequence may require extensive investigations. Choosing the best sequence among all the possible sequences, for a specific objective, is of non-deterministic polynomial time hard, also referred to as NP-hard, problems. This means that the solution can not be found in polynomial time. The time required for a computer to solve a problem, where the time is a simple polynomial function of the size of the input, is referred to as polynomial time. This aspect, together with the assembly complexity makes the sequencing a time-consuming and challenging task.

While the non-rigid behavior of the assemblies depends on different material properties of the individual parts, the fundamental approach to model this behavior is common among different material types. The contribution of this thesis is mainly governed around the sheet metal assemblies. The assembly process of such assemblies is further described in the following.

1.1.1 Sheet metal assemblies

The sheet metals are the dominant material for body structures of the transportation means, namely, automobiles, airplanes. Sheet metals assemblies are referred to as compliant, i.e. they bend and deform during the assembly. Different joining operations are used to join the sheet metal parts. Spot welding and riveting are among the most common point-based joining processes for sheet metal assemblies. In these processes, ideally, at the exact location of the joint, the parts are being connected. All the degrees of freedom (DoF) are being locked at the joint position. Joining sequences on the compliant assemblies are taken into consideration for further evaluation. In the automotive industry, within the production line, the joining stations are organized into geometry stations and re-spot stations. In the geometry stations, the individual parts and sub-assemblies are assembled by spot welding. In this station, the geometrical quality of the assembly is determined, and later the assembly is moved and reinforced in the downstream re-spot station. In the re-spot station, usually, a larger number of weld points are set on the assembly.

Figure 1.1 shows the schematic view of a geometry assembly cell, virtually, where multiple robot arms are operating, assembling the parts together. In this setup, the parts are being picked by a gripper and positioned into the fixture. The welding is performed by a robot arm holding a welding gun. After welding the assembly is being transferred to the transportation rack.
This process, in a more generic manner, can be divided into four main steps:

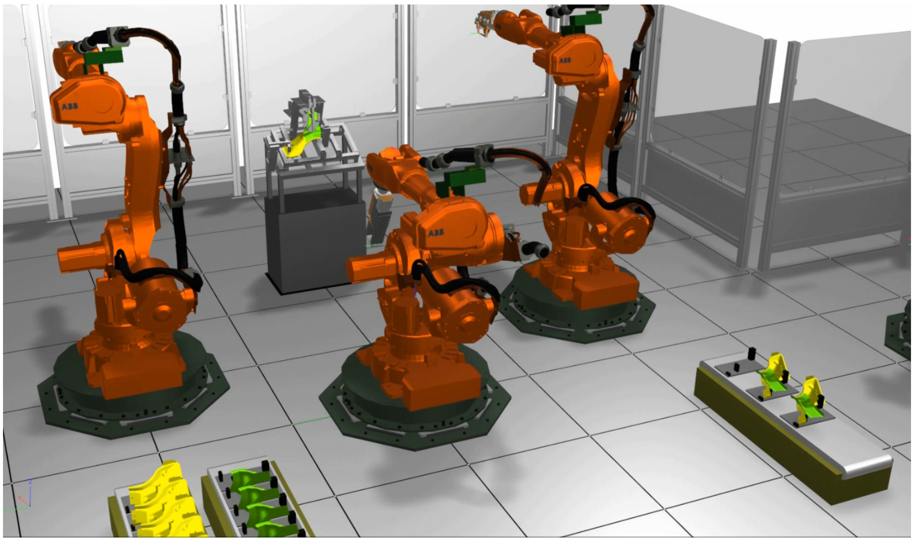


Figure 1.1: Assembly Cell

1. Placement of the parts in a fixture. Fixtures are used for repeatability and accuracy of the produced batch assemblies. Since the fixtures are rigid and stable, they enable repeatable processes, allowing the automation of the assembly process.

2. Clamping the parts together. In this step, the parts are forced into their nominal position. The clamps also constrain the movements of the individual parts, due to external forces, such as gravity or welding gun forces. Bending occurs, and internal stresses are built up in this step.

3. Joining the parts together. In this step, the parts are joined together. Just like the clamping step, bending, deformation and internal stresses are exposed to the assemblies during this operation. The dominant joining method is resistant spot welding (RSW). In this joining operation, two electrodes push together two, or multiple, sheets to be welded on a specific point. When the parts are in contact, a large electric current bypasses the particular spot until the parts are melted and connected, forming a weld. Two different gun types are often used in this process. Figure 1.2 is a simple schematic representation of the differences between the two gun types. In the position gun, Figure 1.2a, one electrode is fixed on one side of the sheet, and the other electrode applies the force. In the balanced gun, Figure 1.2b, equal forces are applied by both of the electrodes. However, the application of the balanced gun is more challenging on the areas close to the curvatures, where tangential forces are acting, and force loss is expected. The changes in the RSW forces, affect the local geometrical quality of the welds.
   Under-weld or expulsion conditions might also occur during the spot welding affecting the quality of the welding. Welding process parameters, such as applied current, squeeze time, clamping forces, welding time, electrode diameter, and sheet thicknesses as well as material properties, determines the quality of the weld, and need to be accurately controlled. The weld points are welded one by one in a sequence. The sequence, with which this process is performed, have a significant impact on the geometrical deviation of the assembly. Therefore, the sequence of joining in the assembly process needs to be controlled.

4. Release from the fixture and springback. After the joining process is completed the assembly is released from the fixture. The internal stresses that are built up during the steps above result in the springback of the assembly.

Within such a setup, non-nominal parts and processes result in deviated assemblies, causing functional and aesthetic problems in the final product. Previous manufacturing processes that individual parts have been through, like stamping and forming, result in parts that have variations from the nominal geometry. In addition, the assembly process itself contributes to the final variation, with disturbances stemming from fixtures, robots, operators, and other involving parties. As a result, these variations in form and dimension stacks-up and, the final assembly varies from its nominal geometry. In the downstream processes, with the variation in the sub-assemblies, assembly process issues may also arise while connecting the sub-assemblies.

The main challenge is how to control the assembly process in a way that the final product does not get influenced by the deviation and ultimately variation. This aspect has brought up the robust design mindset in the manufacturing industry.

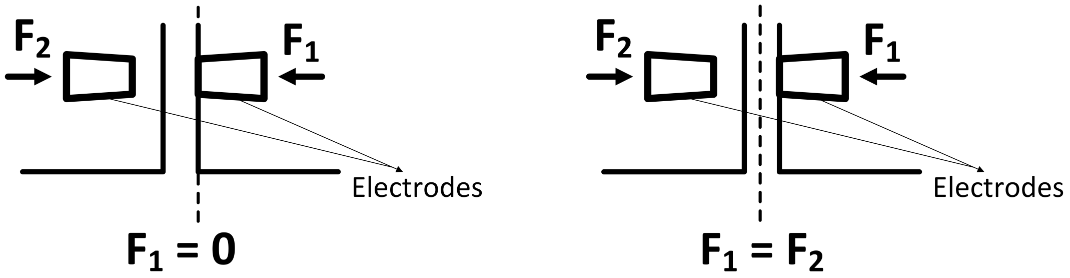
1.1.2 Robust design and tolerancing

To handle variation and allow mass production with interchangeability among parts, the designer specifies tolerances on all critical dimensions. The tighter the tolerances, the more precise processes required to achieve the final demands on the assemblies. To evade tighter tolerances, and exponential increase of the cost, a robust design is desired, a design that is insensitive to variation. In other words, although the geometrical variation exists in the parts and the processes, the final geometrical demands can be met, with a robust design.

The tolerances are defined on the critical dimensions, and they are referenced to a datum system. This means that the reference for the measurement of the tolerance is from the defined datum points. Locating schemes in the sheet metal assemblies, also referred to as datum and master location system (MLS), give meaning to geometrical tolerances. Defining robust positioning points on the parts and assemblies results in reduced amplification of the geometrical variation and thereby a more robust product.

For repeatability, the locating schemes of the parts are intended to be kept constant during all the assembly stages. In other words, the locating scheme, represented by an assembly fixture and a measurement fixture, should have the same coordinates of the locating points as the positioning of the part in the final product.

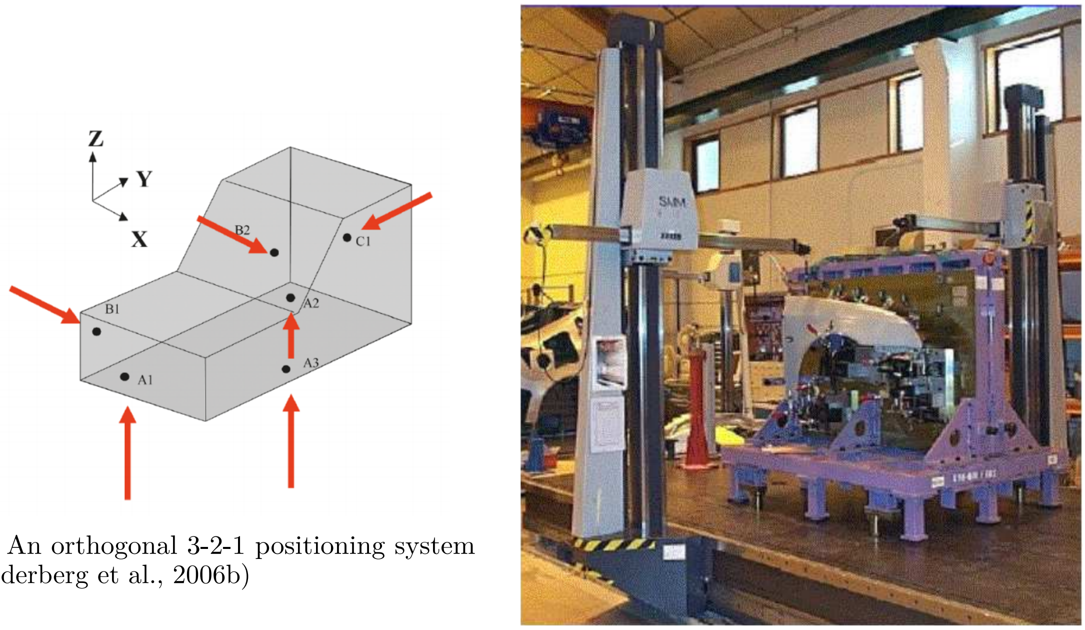
The definition of the positioning and clamping points are defined by the locating schemes to control the position of the parts during assembly. The 3-2-1 locating scheme, that is commonly applied to lock the geometry of the rigid parts, is the fundamental element of the locating scheme in the non-rigid parts. Figure 1.3a



(a) Position weld gun

(b) Balanced weld gun

Figure 1.2: Applied forces in different RSW gun. The picture is inspired by (Dahlström, 2005).



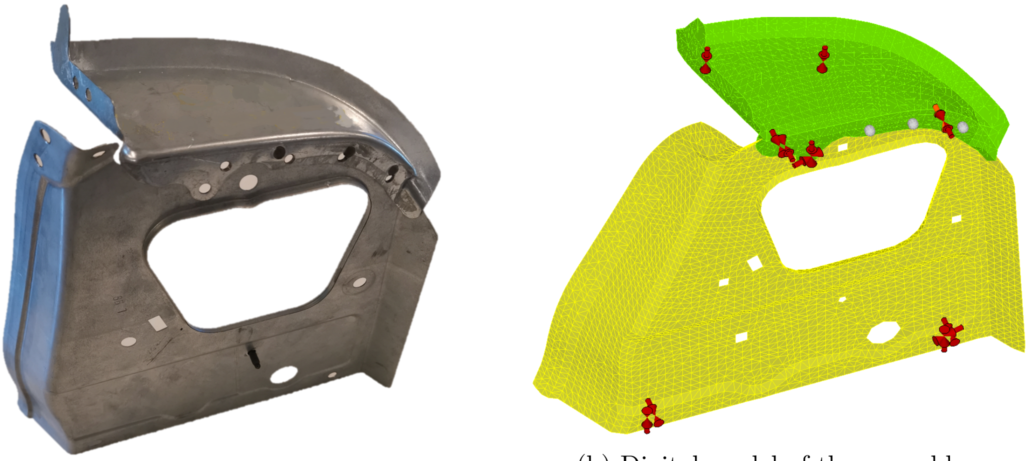
(a) An orthogonal 3-2-1 positioning system (Söderberg et al., 2006b)

(b) A Non-orthogonal over-constrained positioning system (Wärmefjord, 2011)

Figure 1.3: 3-2-1 and over-constrained positioning systems

shows the principle of the locating scheme, where the three A points (A1-A3) lock translation in the Z axis, and rotations along the X and Y axes. The B points (B1-B2) lock the translation in the X axis and rotation along the Z axis. Finally, the C1 point locks the final translation in the Y axis. In this way, all six degrees of freedom are locked for a rigid body in a three-dimensional space. The position of these points plays a crucial role in the amplification of the variation in an assembly. Support elements, including clamps, are often used to force the sheet metal parts into the nominal shape during the assembly. These supports change the positioning system of the non-rigid parts to an over-constrained system, referred to as N-2-1. Figure 1.3b shows a sheet metal part in a measurement fixture. In this case, several clamps have been applied to the assembly forcing the part into the nominal shape.

The optimal position of the locators allows the part tolerances to be relaxed; in other terms lower manufacturing costs are required to produce the single parts. Similar to the part tolerances, the joining process parameters are also interconnected with the positioning system. Joining operation of a non-robust positioning and clamping conditions, result in amplified variation in the final assembly. Figure 1.4 shows a typical body-in-white assembly. The red arrows show the positioning system of the assembly in the digital model, Figure 1.4b. The spot welds have also been shown with the grey spheres. The joining operation parameters, namely, the number of the weld points, position of the weld points relative to the positioning system, and the sequence of welding have an impact on the geometrical outcome of the assembly.



(a) A physical assembly

(b) Digital model of the assembly

Figure 1.4: A body-in-white assembly

1.1.3 Geometry assurance

Satisfying the geometrical requirements defined on the designed products is one of the main challenges of the manufacturing industry. Anomalies in the parts to be assembled and the disturbances during the assembly process lead to non-nominal assemblies. Geometry assurance is referred to as the activities practiced to secure the geometry of the products during the development phases. Söderberg et al. (Söderberg et al., 2016) have developed a virtual tool-box to support the activities that are performed during all the stages of the product development cycle, Figure 1.5. During the early concept phases, robust locator design and variation simulation are used to ensure the robustness (insensitive to geometrical variation) of the designed products. Early in the verification phases, joining simulations can be performed to evaluate the assembly process of the non-rigid bodies. Inspection preparation for accurate programming of the coordinate measurement machines (CMM) and the scanners can also be performed. Later the assembled products are being inspected physically, and the corresponding data are being stored in measurements databases. This data can be used for root cause analysis of geometrical problems in the production phases. With the recent application of the digital twin, the produced data can be used to steer the production line using digital twins. Within the verification phases and the production, the joining simulation can be performed. The spot welding simulation for the geometrical outcome is often performed while the sequence of the spot welds is neglected. The time requirement of this sequencing task is the main reason for simultaneous welding simulation approach, where no sequence is considered for welding. The traditional methods, for spot welding sequencing are sequencing based on the line balancing requirements, and tacit manufacturing knowledge deciding the most critical weld points to be welded first. However, the integration of the sequence analysis in a digital twin context is necessary for accurate steering of the assembly process, representing the physical assembly setup. Theoretically, the simulation of sequences for the optimization purposes requires infeasible and comprehensive Finite Element Analysis (FEA) calculations.

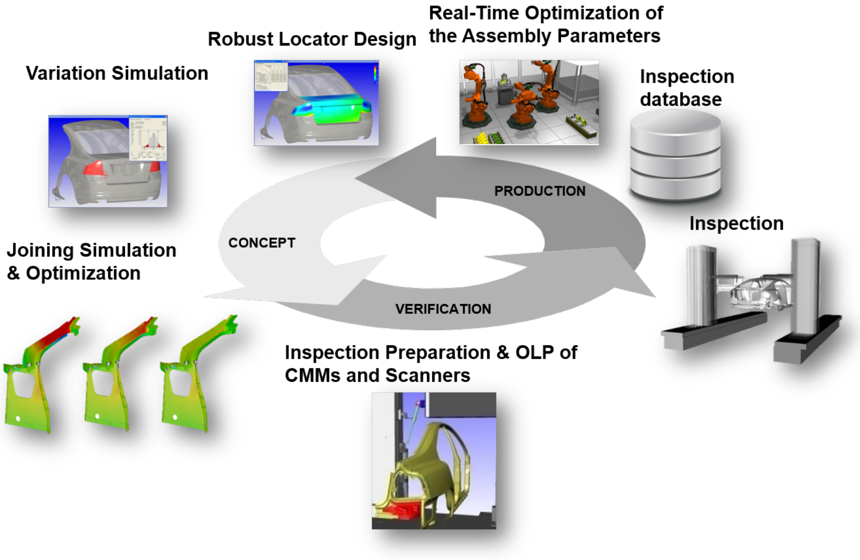


Figure 1.5: Virtual geometry assurance toolbox. The picture is adjusted from (Söderberg et al., 2016).

1.1.4 Self-compensating assembly line

In the manufacturing industry, often the geometrical problems are discovered during the pre-production and physical prototyping phase. Late identification of the geometrical problems gives rise to several design and manufacturing changes, causing massive delays and costs as a result. To be able to adjust and steer the assembly line based on the existing error on the parts, Söderberg et al. have introduced the concept of a self-compensating assembly line for real-time geometry assurance in an individualized production (Söderberg et al., 2017). Figure 1.6 presents the overall layout of such an assembly cell. The incoming parts are scanned initially. Using this information, the parts are sorted and classified based on their quality criteria. Later, the parts are being selectively chosen for the perfect fit, based on the quality criteria, this approach is traditionally being referred to as selective assembly. Within the assembly cell, the assembly parameters are being optimized for the optimal geometrical quality. Spot welding sequence optimization takes place within the assembly cell. To perform the real-time optimization, a CAT-tool is in interaction with an optimizer within the analysis module. Using the information of the scanned parts, from the database, the sequence of the welding is being optimized for each individual assembly. The outcome of the assembly is later being scanned and used in the feedback process.

The self-compensating assembly process is in line with the concepts of the industry 4.0 for sorting and self-adjusting equipment, which improves the quality without tightening the tolerances. The concept utilizes information about individual part (sensing) to be joined, to optimize the parameters for each individual (thinking) and to perform the assembly process with the provided optimal parameters (acting), and feedback for eventual automatic adjustments. The smart system utilizes product and process knowledge as input to an interlinked approach where the conditions for each individual product are optimized in order to reach the highest quality with limited resource consumption.

In this thesis, the expertise of geometry assurance will be exploited to develop an assembly cell that can adjust to the individual parts to minimize the geometrical variation in the assembled products through the efficient joining processes.

1.2 Research Project

The research project, in which this research is carried out, is entitled "*Smart Assembly 4.0*", conducted in collaboration with the Wingquist Laboratory and the Area of Advance Production at Chalmers, financed by The Swedish Foundation for Strategic Research. The vision for the project is an autonomous, self-optimizing robotized assembly factory, which maximizes quality and throughput, while keeping flexibility and reducing cost, by sensing, thinking, and acting strategies. The main goal of the project is to develop new methods and a demonstrator showing the vision of the Smart Assembly 4.0 and self-compensating assembly lines for complex products. The goal is also to show and quantify the positive impact on quality, throughput, equipment utilization, flexibility, and cost.

1.3 Scope

In line with the vision of the research project, the purpose of this thesis is to show the vision of a self-optimized robotized smart assembly for complex products, through the applications of the self-optimized joining processes. The purpose is also to minimize the effect of variation in the final assembly. Among the joining parameters in the compliant variation simulation, the sequence of the joining is studied for real-time applications.

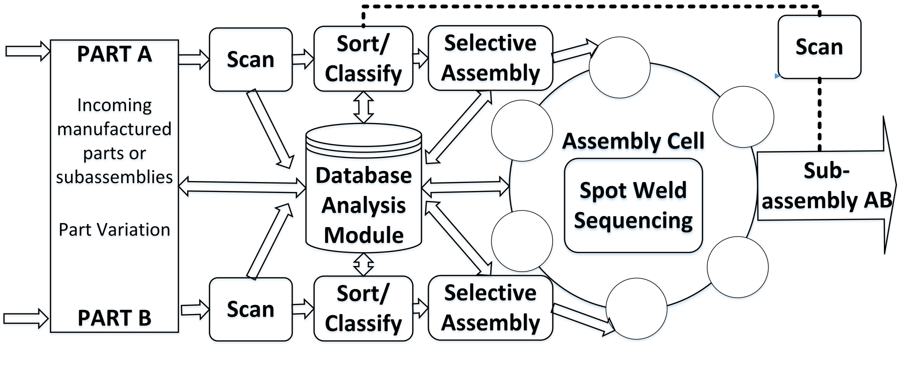


Figure 1.6: Self-compensating assembly line. The picture is inspired (Söderberg et al., 2017).

Theoretically, joining sequence optimization is a non-deterministic polynomial-time (NP) hard combinatorial problem. To solve such a problem in real-time, for accurate geometrical quality of the sheet metal sub-assemblies, to minimize geometrical variation or deviation in the assemblies are the goals of the research. Application of the proposed methods, by means of an algorithm, within the context of the self-compensating assembly cell, is also within the scope of this research.

1.4 Research Questions

Based on the presented research scope and goals presented earlier, the following Research Questions (RQ) are formulated:

RQ 1: *What problem formulations are considered for joining sequence optimization with respect to the geometrical quality?*

RQ 2: *How can spot welding sequence be optimized with respect to the geometrical variation of the assembly?*

RQ 3: *How can spot welding sequence be optimized with respect to the geometrical deviation of the assembly in a self-compensating assembly line?*

1.5 Delimitation

The joining sequence optimization is the focus of this research. Within the joining processes, only the spot welding operation has been analyzed. Within spot welding, several parameters are affecting the geometrical outcome of the joining process. The heat exerted to the parts during the welding will cause local deformation in the joining points and eventually result in material shrinkage.

In this research, the applied simulation method is built upon linear FEM, using linear material models and infinitesimal strain assumptions, considering neglectable local weld deformation compared to the whole assembly. Non-linear material models and the thermal effect can be considered while retrieving the geometrical outcome of the assembly in the simulation, with the trade-off of the simulation time. Today, with the available computational power, this approach is infeasible, for sequence optimization. However, there is no evidence empowering the accuracy of simulation considering the heat, over the applied approach, for spot welds.

Moreover, in all the studies, the geometrical outcome of the assemblies are retrieved while the sound weld quality is considered for all the weld points. All the weld points are considered to be functional, locking all the degrees of freedom in the joining point. In reality, force losses during welding can result in weld bead defects, making them nonfunctional.

Due to the combinatorial nature of the problem, the proposed optimization approach is simulation-based. Performing physical experiments for all the possible alternatives are infeasible. However, experimental data can also be used in the proposed algorithms for retrieving the geometrical outcome of the assembly.
Other joining methods on different material types have not been analyzed in the presented studies.

1.6 Thesis Structure

This thesis is structured based on two parts, Part I Introductory Chapters, and Part II Appended Papers. In the Introductory Chapters part, the first chapter provided the background to the research topic, the research scope and the research questions are presented. The second chapter discusses the frame of references on which this thesis is based on and critically addresses the relevant research. Chapter 3 introduces the research methodology and the methods applied in this thesis. Chapter 4 presents and summarize the results achieved in the presented research. Chapter 5 discusses the achieved results, and the answers to the research questions are provided. In Chapter 6, the conclusions are drawn upon the presented analysis of the results, and the future work is discussed.
Part II presents the appended papers, upon which this thesis is built. The details of the results can be found in the corresponding papers.

Chapter 2

FRAME OF REFERENCE

The frame of the reference in this thesis is governed around the product realization loop and the corresponding activities that are performed to realize and secure the geometry of a product, as introduced in Chapter 1.1.3, Figure 1.5. The aim of the geometry assurance is to assure the geometrical quality of the products. The fundamental pillar of this process is based on the robust design principles. Thereby, initially, robust design is addressed. The robustness of the part and the geometrical variation of the part are closely interconnected with the positioning of the part in space, which is often referred to as locating scheme.

The second section introduces the locating schemes. As introduced earlier, the definition of geometric tolerance requires a reference. In other words, the locating schemes are a necessary foundation for geometrical tolerancing, which is addressed in the third section. Followed up by the statistical basics and definitions in the fourth section, the computer-aided tolerancing principles are introduced in the fifth section. Built within the CAT tools, compliant variation simulation, and state of the art to retrieve the geometrical outcome of the assemblies after joining, are presented. The nature of the problem under study in this thesis lies within the combinatorial optimization category, addressed in Section 2.7. Finally, the main contribution of this thesis lies within the joining sequence optimization, addressed in Section 2.8.

2.1 Robust Design

A design that is insensitive to geometrical variation is defined as a robust design, in this thesis. Based on the Taguchi quality principles, control factors, and noise factors are affecting the design concept (Taguchi, 1986). Figure 2.1 is a block diagram representation of a product or process. The response of the product is the output. This output in the robust design context can be considered as the quality characteristics. The signal factors are the inputs to the system by the users. The noise factors are the parameters that cannot be controlled by the designers. The control factors can be specified and manipulated by the designers and are easy to control. To optimize the quality characteristics in the robust design process, the control parameters should be

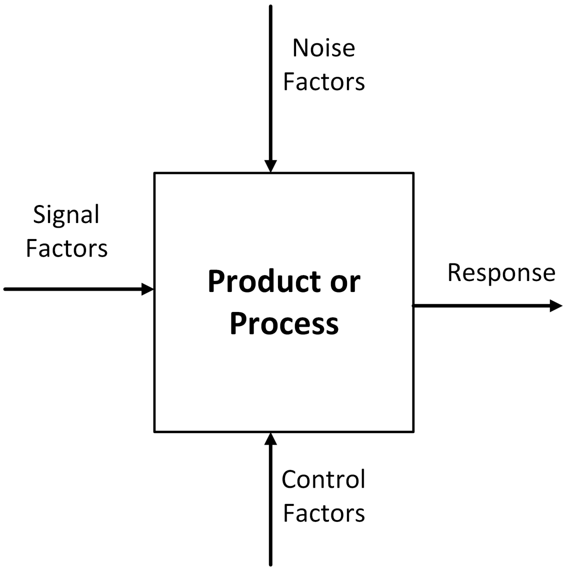


Figure 2.1: Robust design in a system perspective (Phadke, 1995)

chosen in a level where the expected loss caused by the noise factors are minimized (Taguchi, 1986). Applying this system perspective to the geometry assurance process for sheet metals, the locating schemes are considered as the control factors while the part variation is the noise factor (Söderberg & Lindkvist, 1999).

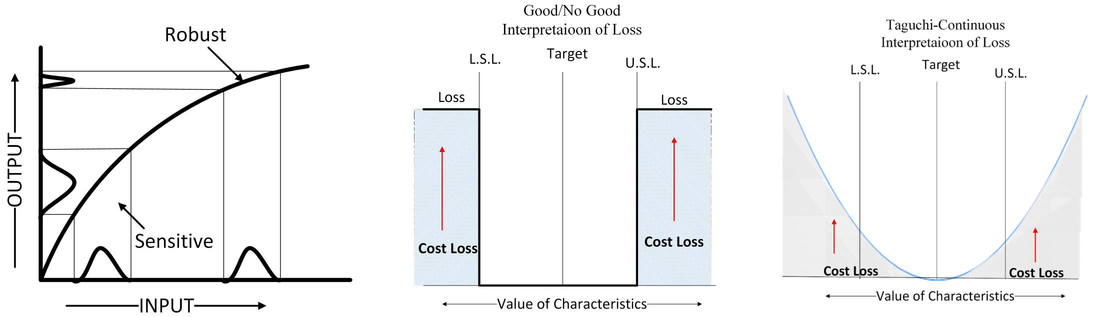
Disturbances and noise factors, which may result in geometrical variation, exist in all the manufacturing processes. Therefore the control factors in the design concept should be chosen in a manner so that the product (assembly) is robust. However, the manipulation of these factors depends on the existing processes and the interlinked parameters. Figure 2.2a shows the input-output perspective on the robustness curve, considering the input value as the control factors and variation in the input as the noise factors. By increasing the nominal settings of the control factors, the variation in the response of the systems will be decreased (Taguchi, 1986).

As mentioned previously, Section 1.1.3, geometry assurance activities are designed to reduce the effect of variation in the products, to achieve better geometrical quality. Taguchi has introduced a way to interpret quality, considering quality loss (Taguchi, 1986). He proposes that the deviation of the performance characteristic and its effect on the cost due to quality loss follows the quadratic approximation:

$$L(Y) = f(Y - T)^2 \ , \tag{2.1}$$

where $L(Y)$ is the cost loss, Y is the performance characteristic, and T is the target value. This interpretation of continuous loss function is shown in Figure 2.2c. This perspective has created a niche in quality control, compared to the previous good or no good interpretation of quality loss, represented by a step function 2.2b.

Phadke has proposed a three step approach to achieve a robust design (Phadke, 1995). Concept design, where different technologies and tools are used to achieve a specific function of a product. Parameter design, where the best settings for the



(a) Sensitive and robust concepts (b) Good/No good interpretation of loss (c) Taguchi continuous interpretation of loss

Figure 2.2: Principles of robust design. The picture is inspired by (Taguchi, 1986).

control factors are determined. Finally, tolerance design, where a trade-off between the quality loss and manufacturing cost is being made. It has been argued that the dominant focus of the robust design approach is on parameter design. Thereby, the control factors in the geometry assurance context, namely, the locating schemes are discussed for achieving a geometrically robust assembly. In this thesis, the joining operation setting, such as the sequence of the welding, which was considered to be a noise factor of the robust design process and hard to control, will be introduced as a controllable factor.

2.2 Locating Schemes

Locating schemes are positioning and supporting the parts during the manufacturing processes and inspection activities. Moreover, they can also define how the parts are assembled in the final product. For instance, the position of the holes and screws are decided by the locating system. As introduced in the previous chapter, the locating schemes play a crucial role in the robustness of the product. Thus they are the main focus in the geometry assurance process.

Figure 2.3 visualizes the realization of a 3-2-1 locating scheme between two sheet metal parts. The three pins, points A1-A3, are used to lock the translation in Z direction and rotation along the X and Y axes. The two-direction steering pin and hole and the one-direction steering pin and slot, points B1-B2, lock the translation in X direction and rotation along the Z axis. Finally, the two-direction steering hole and pin, point C1, locks the translation in the Y direction. This way, all six degrees of freedom will be locked between the two components in a three-dimensional space. As visualized in Figure 1.3a, this system represents an orthogonal 3-2-1 locating scheme. In a non-orthogonal scheme, the directions of locking the DoF are not necessarily orthogonal to each other. Söderberg et al. have defined different types of locating schemes, as 3-2-1 orthogonal, 3-point orthogonal, 3-directions non-orthogonal, 6-direction non-orthogonal, and N-2-1 orthogonal or non-orthogonal (Söderberg et al., 2006b).

In the sheet metal assemblies, the locating schemes are often over-constrained

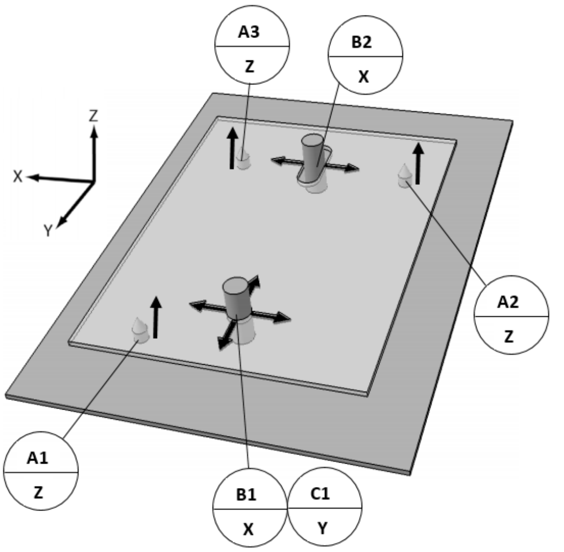


Figure 2.3: Realization of a locating scheme. The picture is adjusted from (Wagersten, 2013).

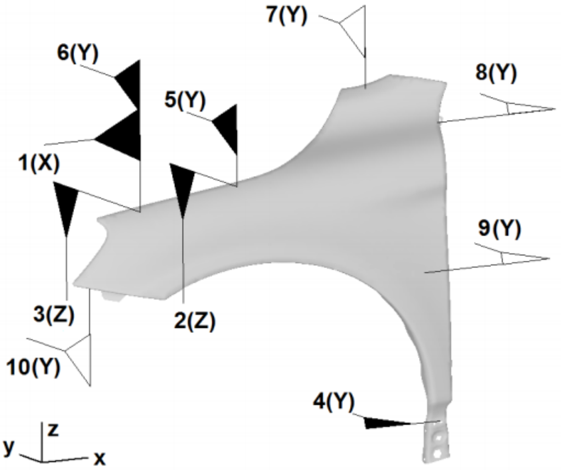


Figure 2.4: An example of N-2-1 locating scheme (Wagersten, 2013)

due to the compliant behavior of the material. To compensate for the additional forces, such as gravity, during the assembly, the locating scheme will be expanded to N-2-1, where N> 3, to increase the support in the planar adjacencies between the compliant components (Cai et al., 1996). Figure 2.4 shows a 7-2-1 locating scheme of a complaint sheet metal part. To realize such a locating scheme, four support points, in the form of clamps, are needed to assist the assembly process in the Y direction. The geometrical outcome of the assemblies is sensitive to the positions of these locating points. Any deviation in any of the locating points will result in a deviated assembly after joining (Söderberg & Lindkvist, 1999). To retrieve the sensitivity of a specific measure to the deviation in the locating scheme, the following linear relationship is built (Söderberg & Carlson, 1999):

$$d_m = A\delta_{lp} \tag{2.2}$$

where d_m is the deviation of a defined measurement point in a specific direction, δ_{lp} is the deviation in the locating scheme, and A is a matrix in which each row connects the locating scheme matrix to the coordinate and direction in the specified measure. For details, see (Söderberg & Carlson, 1999).

Adding the extra constraints to the assembly process increases the potential of increased variation in the geometrical outcome. As an example, exposing the assembly to multiple clamps, results in more inaccuracies due to the applied clamping forces and sequences applied during the assembly (Xie & Hsieh, 2002).

2.3 Tolerancing

Tolerances are crucial for producibility and cost of the manufactured products. The research within the filed of tolerancing has been developed and matured during the years, mainly after the industrial revolution. Hong and Chang have performed a comprehensive review of the research within tolerancing (Hong & Chang, 2002). They have shown that extensive research have been conducted within the fields of tolerance definition, allocation, analysis and, evaluation. Several studies have divided the tolerancing research into the definition, application, and production (Hong & Chang, 2002; Shah et al., 2007).

The focus on tolerance definition is on accurate representation and categorization of the intended tolerances on the products. The tolerance application field discusses the tolerance analysis aspects, in terms of allocation and cost and losses. The tolerancing in production focuses on the process control parameters and root cause analysis of the failures to satisfy the requirements (Dahlström, 2005).

The context of the presented thesis lies more towards the tolerance application field of research. Tolerances on a complete product are to be allocated and analyzed in a top-down or bottom-up perspective. In the top-down perspective, the tolerances are broken down from the final requirements to the detailed tolerance specification on each individual component. The advantage of this approach is that the importance weights can be given to the critical areas in the final product and thereby, tighter tolerances will be assigned to the corresponding components. Comprehensive studies have been made on this approach (Lööf et al., 2007; Söderberg, 1993, 1995).
In the bottom-up perspective, the general tolerances based on standards, or tacit manufacturing knowledge is applied to the components and eventually leads to the tolerance specification on the final product.

The tolerance analysis methods for the rigid-bodies, in either of the approaches, are divided into the worst-case stack-up analysis, statistical, and sampled methods

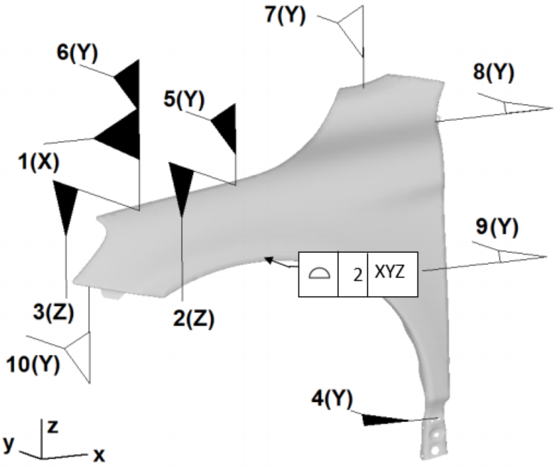


Figure 2.5: An example of a geometric tolerances. The picture is adjusted from (Wagersten, 2013).

(Chase & Parkinson, 1991). In the next section, some of these methods are introduced. As mentioned previously, Section 1.1.2, the locating schemes are often used to refer the geometrical tolerances to a point of reference. While verifying the defined geometrical tolerances, the locating points are active, and the parts should be positioned in the specified points. Figure 2.5 visualizes a definition of surface requirement on a sheet metal assembly. As the requirement specifies the specified surface can vary within two millimeters while the part is being held in the specified locating scheme. The physical setup of a similar part while it is being held in the fixture with the specified locating scheme for inspection, is shown in Figure 1.3b. Any disturbances in the locating scheme will directly affect the defined tolerance based on the linear relationship provided in Equation (2.2).

2.4 Statistical Tolerance Analysis

The previous reviews within the tolerance analysis field have identified different statistical tolerance analysis methods (Kumar & Raman, 1992). In general, these approaches can be divided into stochastic analytical and stochastic sampled methods. The main challenge in the tolerance analysis is to predict the moments of the distribution of the assembly. The four moments of distribution have been introduced as the mean, variance, skewness, and kurtosis coefficients (Nigam & Turner, 1995). Most of the tolerance analysis methods express the assembly response t_f as a function of the tolerances of the n components in the assembly $(t_1, \dots t_n)$:

$$t_f = f(t_1, t_2 \dots, t_n) \tag{2.3}$$

Prior to introducing these techniques, the basic statistical terms and definitions are presented for the ease of understanding. The terms and definitions are based on (Montgomery & Hoboken, 1994).

First of all the mean value of the sample $x_1, \ldots x_n$ is calculated as:

$$\bar{x} = \frac{1}{n}\sum_{k=1}^{n} x_k \tag{2.4}$$

The variance of the same sample can be calculated as:

$$s^2 = \frac{1}{n-1}\sum_{k=1}^{n}(x_k - \bar{x}) \tag{2.5}$$

The standard deviation based on the calculated variance is:

$$\hat{\sigma} = s = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x_k - \bar{x})} \tag{2.6}$$

The normal distribution is extensively used and referred to within the tolerancing research. The probability density function of the normal distribution is:

$$f(x|\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \tag{2.7}$$

where μ is the population mean.
Most of the tolerances on the parts are defined considering the normal distribution of the variation. According to the central limit theorem, even if the parts are manufactured by processes not following the normal distribution, with the sufficient number of parts, the response on the of the stack-up function will be approximately normal (Nigam & Turner, 1995).

In order to control the process variation, the six sigma tools have been introduced. Within this tool, the process capability index (C_p) is an indicator of the process performance (Taguchi & Chowdhury, 2004). This index, where USL and LSL are the upper and lower specification limits, is calculated as:

$$C_p = \frac{USL - LSL}{6\sigma} \tag{2.8}$$

To estimate the process capability, taking into account the un-centered mean process, the adjusted capability index C_{pk} is introduced. This index is a measure for both the process variation, similar to C_p, but also gives information about the location of the variation, in the sense of mean shift.

$$C_{pk} = min\left\{\frac{USL - \bar{x}}{3\sigma}, \frac{\bar{x} - LSL}{3\sigma}\right\} \tag{2.9}$$

Figure 2.6 shows the difference between different values for C_p and C_{pk}. Figure 2.6a shows the same value for the two indices while the mean value is centered between the specification limits and also lies between the two. In 2.6b, the process is off-centered and the mean is shifted. In this case, the C_{pk} index can provide this information.

However, the C_p value is still constant, as it is only a measure for variation. In (c) and (d) the changes in the variation is captured by both of the indices (Kane, 1986).

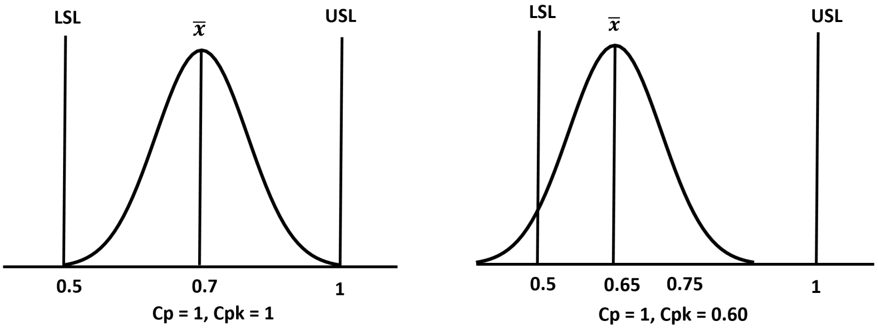
With the provided basics statistics, the tolerance analysis techniques are introduced in the following.
The most traditional approach is the worst-case 1-dimensional stack-up analysis. In this approach, the maximum tolerances (t_p) in one dimension for all the parts ($p1 \dots p_n$) are added together to reach to the final tolerance on the assembly (t_f):

$$t_f = \sum_{p=1}^{n} t_p \tag{2.10}$$

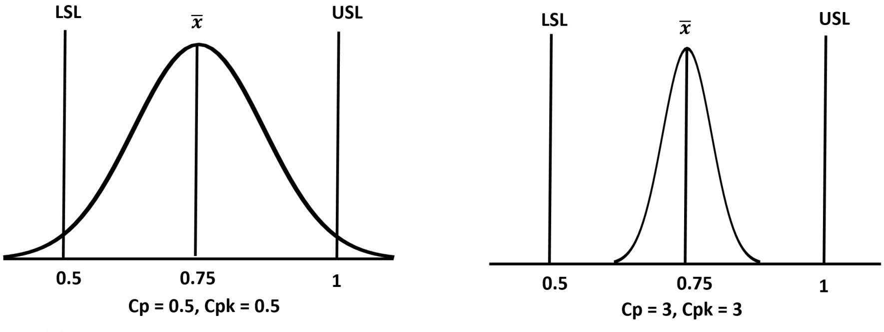
The probability of the occurrence of the worst case for all the parts is small and, thereby, such a technique is unrealistic and may result in cost loss.
The root sum square (RSS) method and combinations of the worst-case and RSS have also been introduced for not considering solely the worst-case.

$$t_f = \sqrt{\sum_{p=1}^{n} t_p^2} \tag{2.11}$$

Spotts' modified model and modified statistical model are built upon the same principles (Kumar & Raman, 1992).
To include the mean shift of the process into the tolerance analysis models, the mean shift model is introduced (Chase & Parkinson, 1991). In this approach an



(a) $C_p = C_{pk}$ inside limits (b) $C_p > C_{pk}$ outside limits



(c) $C_p = C_{pk}$ outside limits (d) high C_p and C_{pk}

Figure 2.6: Interpreting C_p and C_{pk}

estimated mean shift factor (m_p) between zero and one is considered for each part of the assembly.

$$t_f = \sum_{p=1}^{n} m_p t_p + \sqrt{\sum_{p=1}^{n} ((1 - m_p)t_p)^2} \tag{2.12}$$

The Taguchi 6σ approach assumes a normal distribution for assembly tolerance (Nigam & Turner, 1995; Taguchi & Chowdhury, 2004). Having the mean of the process for each part as μ_p, and the final assembly mean variation, μ_f, then $\mu_f = \sum_{p=1}^{n} \mu_p$. The standard deviation of the final assembly, σ_f, can be calculates as $\sigma_f^2 = \sum_{p=1}^{n} \sigma_p^2$, and $\sigma_f = \sqrt{\sum \sigma_p^2}$. Now if each part is produced in 6σ quality (corresponds to 99.99973% acceptable parts), the resulting assemblies will have 2.7 defects per million. Based on the original Taguchi method, a product Gaussian quadrature method is introduced. In this method, using the high and low levels of $\mu_p \pm \sigma_p(\sqrt{3})$ and considering a weight of 1/6 for the high and low levels and 4/6 for the center level, correct values up to the fifth moment for linear functions can be achieved (Nigam & Turner, 1995).

More analytical Taylor series expansion of different orders of the assembly response function (Cai et al., 2005; Evans, 1975; Nigam & Turner, 1995) have also been addressed in the literature. An extended Taylor expansion method is represented as (Nigam & Turner, 1995):

$$\begin{aligned} t_f =& f(\mu_1, \ldots \mu_n) + \sum_a (t_a - \mu_a) f_a \\ &+ \frac{1}{2!} \sum_{ab} (t_a - \mu_a)(t_b - \mu_b) f_{ab} + \ldots \\ &+ \frac{1}{5!} \sum_{abcde} (t_a - \mu_a)(t_b - \mu_b)(t_c - \mu_c)(t_d - \mu_d) \\ &\times (t_e - \mu_e) f_{abcde} + O[(t - \mu)^6], \end{aligned} \tag{2.13}$$

where f_a, f_{ab}, and so on, are the partial derivatives of f with respect to t_a, t_b, evaluated at $t_i = \mu_i$.
The above mentioned analytical methods are computationally inexpensive. However, the challenge of computing the derivative of the Taylor series may lead to complex algebraic manipulation. Moreover, it is uncertain that using the analytical methods, the accurate representation of the assembly behavior is achieved (Cai et al., 2005).

Other numerical approaches are involved with sampling strategies using Monte-Carlo simulations. In the Monte Carlo model, random numbers generate part tolerances from the specific part distributions. The assembly response is generated when a large number of iterations are performed. The accuracy of the approach is highly dependent on the number of the iterations considered for the Monte Carlo simulations; thereby, the method is more computationally heavy (Nigam & Turner, 1995). The Monte Carlo model has been used within the computer-aided tools, CAT, to retrieve the assembly response.

2.5 Computer Aided Tolerancing

Over the years several commercial tools have been introduced for estimating the geometrical outcome of the assemblies given the part tolerances. In this work, the commercial software RD&T has been used to retrieve the geometrical outcome of the assemblies (RD&T Technology, 2019). This tool is based on Monte Carlo simulation as introduced above. The functionalities and the capabilities of the tool and the working order within the product realization loop have been introduced by Söderberg et al. (Söderberg et al., 2016).

Starting from the concept phases, stability analysis of the concept is performed. Through this function, the locating schemes are being disturbed, and the response to those disturbances are propagated through the part (Söderberg & Carlson, 1999). Identifying the areas sensitive to variation, the locator optimization is performed to secure the geometry during the manufacturing and production phases. In this task, the location of the locating scheme is optimized for minimum sensitivity.

Later in the concept phases, the variation simulation is performed (Söderberg et al., 2006a). In this analysis, the response of a critical measure in the assembly is estimated, using the Monte-Carlo Simulation. Random numbers are assigned to the part tolerances based on the specified distribution. The locating scheme is also subject to the process and part disturbances. The tolerances can also be assigned to these points. The response of the assembly to the assigned tolerances are calculated, and the distribution of the variation in the specified measure is achieved. Having the USL and LSL, the outcome can be analyzed for acceptance or adjustments of the tolerances.

In case of achieving an assembly outside the specified limits, the contribution analysis is performed to identify the critical tolerances. A list of the most contributing tolerances to the variation in the specified measure will be achieved through this function. The designer can then decide on changing a specific tolerance or readjusting the limits given that the positions of the locators are optimal.

Figure 2.7 shows the analysis of the three mentioned functionalities in the CAT tool RD&T.

2.6 Compliant Variation Simulation

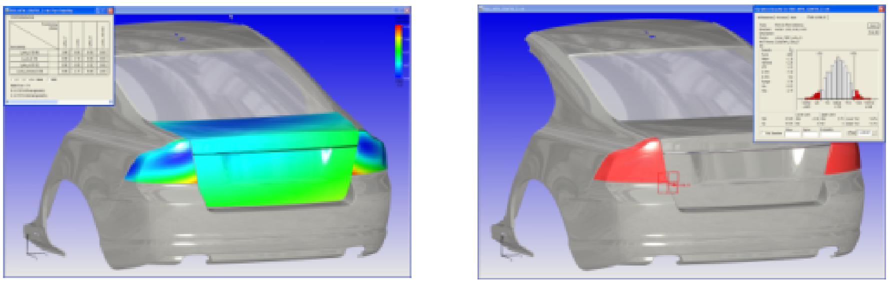
The variation simulation introduced above has been applied to the rigid body assemblies. However, in non-rigid parts, such as sheet metals, the parts are bent and deformed during the assembly. Therefore, the locating scheme can be overconstrained, Section 2.2.

The response of the assembly to the applied forces, clamping, joining, gravity, fixture disturbances, and part variation for the non-rigid parts can be retrieved using

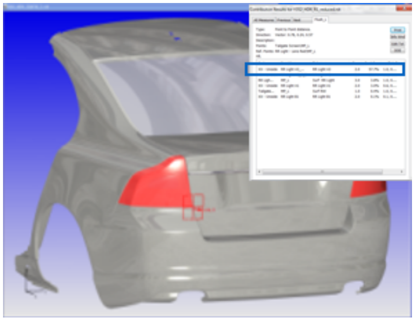
FEM. The FEM solver has been incorporated in the deployed CAT-tool RD&T (RD&T Technology, 2019). The basic idea in the FEM is that the parts are discretized to a mesh, structured by elements. Nodes and vertices define each element. For each of these elements, the deformation after assembly is approximated. The details of the FEM can be found in (Larson & Bengzon, 2013).

A generic approach to get the response of the assembly with respect to the variation is Direct Monte Carlo (DMC) simulation. However, since a large number of iterations is required to achieve satisfactory accuracy in the Monte Carlo simulation, and full FEM problem is solved consecutively in each iteration, the method is time demanding.
A more time-efficient method, compared to the DMC, is Method of influence Coefficients (MIC) (Liu & Hu, 1997). The method is based on small part deviation from nominal assumption and is applicable when the material properties, namely, stress-strain relation, are in the linear range. Considering these aspects, the linear relationships between part deviations and assembly deviations are established. To achieve this, a sensitivity matrix is constructed describing this linear relationship. This sensitivity matrix is then used together with the Monte Carlo simulation iteratively, bypassing the full FEM problem calculation. The main steps of the method for the point-based joining methods, like spot welding, are as follows:

- Positioning and clamping: The parts are being positioned into the fixture, and the errors from the nominal geometry for all the nodes in the assembly are calculated. The deformation of the assembly, (u_{def}), prior to joining, is



(a) Stability analysis (b) Variation simulation



(c) Contribution analysis

Figure 2.7: Different functionalities in the CAT tool. The picture is adjusted from (Söderberg et al., 2006a).

being determined, from the sensitivity matrix (S), $u_{def} = Sd$. Here, d is the displacements of the weld points and clamps.
From this information, the total displacements of all the nodes in the assembly can be calculated, adding up the positioning offset and the deformation of the parts.

- Joining: On the position of the joints, a rigid beam is introduced to the joint pairs locking all the degrees of freedom. The displacements on these points are forced to be zero. The sensitivity matrix is being updated after this operation. The choice of the welding gun affects the applied welding forces, see Figure 1.2.

- Release and spring-back: To retrieve the springback of the assembly, on the position of the clamps, negative clamping forces are introduced to the assembly. The response of the assembly with these forces are calculated, and the final displacements are derived.

One inaccuracy that can arise during this method is the penetration of the adjacent parts into each other. This means that forces that are applied from the interaction of the mated surfaces between each other are neglected. To avoid this problem, and to retrieve more accurate assembly responses, contact modeling has been added to the compliant variation simulation (Dahlström & Lindkvist, 2007; Lindau et al., 2016; Wärmefjord et al., 2008). Through this method, the contact surfaces are being defined using contact nodes on each part. Similar to the first step in the MIC approach, the displacement in the contact nodes are calculated. In case of penetration, the corresponding forces are applied to the model pushing the parts away from each other, until surface to surface contact is achieved. Contact modeling is also performed after the parts are joined together. Since contact modeling is a non-linear method, the MIC, to retrieve the assembly response using contact modelling, behaves non-linearly. Contact modeling also increases the computation-time requirement of the MIC approach. State of the art in the contact modelling with the MIC method is quadratic programming formulation of the contact problem (Lindau et al., 2016). Studies have been made reducing the computation-time needed to retrieve the response of the assembly using MIC and contact modeling (Lorin et al., 2017).

With the combined MIC and contact modeling, the joints can be set at the same time, simultaneously, and the response can be retrieved at once. However, this approach is not realistic and physically infeasible. In a typical assembly station, multiple robot arms are performing the spot welding. However, the number of the weld points are often more than the number of the guns available. Nevertheless, having the same number of the guns and weld points, absolute simultaneity is complex to achieve. Therefore, the sequence of the joining operation becomes a critical parameter to achieve accurate responses (Cai et al., 1996; Liu & Hu, 1997; Wärmefjord et al., 2010). To include the sequence of welding in the compliant variation simulation, Wärmefjord et al. have considered a step-wise approach where the assembly is welded at each point and the MIC and contact modeling is performed (Wärmefjord et al., 2010). They have shown that including the sequence of welding increases the accuracy of the simulations. They have validated the simulation accuracy by comparing the outcome with the physical inspection data. Although the introduced approach increased the accuracy, the intermediate spring-back calculations after each weld point increase the calculation time. To avoid these steps, Lorin et al. have formulated the extended MIC where the intermediate spring-back steps are not performed (Lorin et al., 2019; Lorin et al., 2018).

An overview of the parameters affecting the simulation accuracy is given in Figure 2.8. The focus in this thesis is on joining sequence parameter, which has shown to impact the geometrical outcome of the assembly in the appended papers and the accuracy of the simulation (Wärmefjord, 2011; Wärmefjord et al., 2010). Other studies have intended to extend the MIC method from a single station to a multi-station strategy by the state-space representation of the assembly stations (Camelio et al., 2003).

2.7 Combinatorial Optimization

Optimization is about finding the "*best*" solution among all the possible alternatives. The suitability of the best solution is measured against one or multiple criteria. The general mathematical optimization methods and the algorithms can be divided into various categories, and details of each method is not in the scope of this thesis. For a better understanding of the problem under study and to position the problem in the optimization method categories, a general taxonomy of the optimization methods, based on the optimization textbooks such as (Boyd & Vandenberghe, 2004; Nocedal & Wright, 2006) is given in Figure 2.9. This taxonomy is presented for the purpose of positioning the problem studied in the thesis and is not intended to give a comprehensive overview of the optimization methods. Since the methods can be combined across the categories, several other studies and books can be found categorizing the methods differently. The joining sequence problem is about the selection of the best sequence among, available alternatives, which perfectly fits the definition of the combinatorial problems. Based on the presented optimization taxonomy, the combinatorial optimization lies within the discrete optimization methods.

Combinatorial optimization looks after a solution in a finite set of alternatives. The set of alternatives can be represented by a graph, nodes, and vertices, in its simplest form of representation. The set of alternatives grows exponentially by adding more number of the nodes to the graph. Consequently, examining all the possible alternatives, so called exhaustive search, is infeasible (Schrijver, 2003). One typical problem within this type is the well-known traveling salesman problem (TSP). The TSP investigates the shortest path to visit a given number of cities and return to the original city. This problem is an NP-hard combinatorial optimization problem.

- Simulation Accuracy
  - Assembly sequence
  - Fixturing
    - Fixture repeatability
    - Clamping sequence
  - Joining process
    - Joining sequence
    - Weld location variation
    - Welding gun variation
    - Influence of heat
    - Welding speed
    - Welding direction
    - Contact modeling
  - Modeling
    - Material parameters
    - Material model
    - Mesh quality
    - Numerical accuracy
  - Statistical parameters
    - Inspection data
      - Number of samples
      - Number/position of inspection points
      - Inspection error
    - Predicted data
      - Number of iterations
      - Distributions

Figure 2.8: Parameters affecting the simulation accuracy in variation simulation

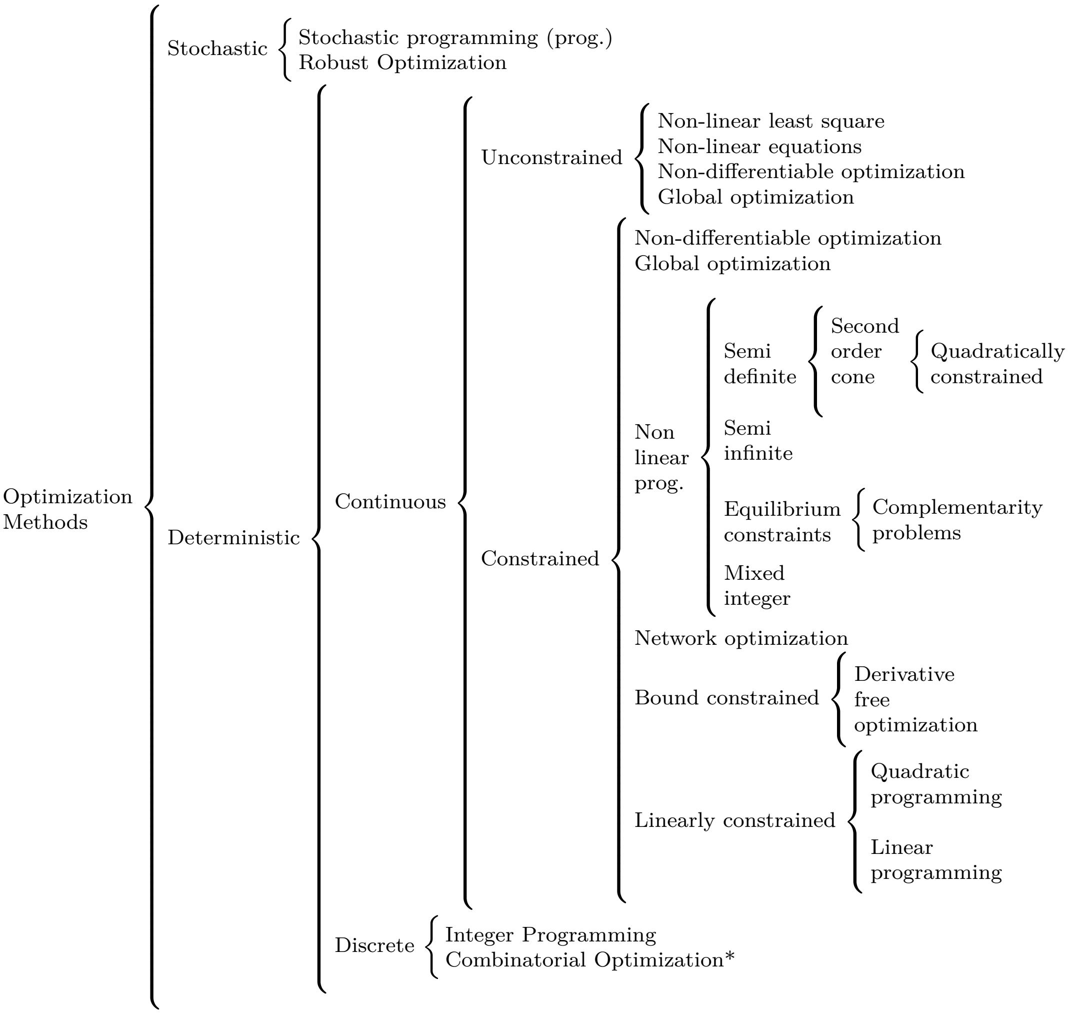
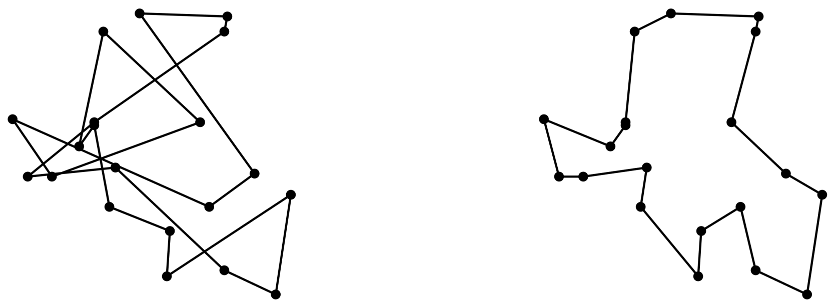


Figure 2.9: Optimization methods taxonomy

A general formulation of this problem is (Dantzig, 2016):

$$
\begin{aligned}
\min \quad & \sum_{i=1}^{n} \sum_{j \neq i, j=1}^{n} c_{ij} x_{ij} & \\
\text{s.t.} \quad & x_{i,j} \in \{0,1\} & i,j = 1 \ldots, n; \\
& \sum_{i=1, i \neq j}^{n} x_{ij} = 1 & j = 1 \ldots, n; \\
& \sum_{j=1, i \neq j}^{n} x_{i,j} = 1 & i = 1 \ldots, n;
\end{aligned}
\tag{2.14}
$$

where c_{ij} is the distance between city i and j, n is the number of the cities to be visited, and x_{ij} is a variable that gets the value one if the path goes from i to j, else zero is assigned to it. Here, the first equality constraint defines each city is visited from one other city. The second equality defines from each city, only one other city can be visited. One other critical constraint that should be considered for this problem is the limitation of the sub-tours. From one city, all the cities should be visited on a single



(a) An alternative path (b) The optimal path

Figure 2.10: An alternative and the optimal path for a TSP with 19 cities

tour. There are various formulations available for this constraint and in general, the TSP problem (Schrijver, 2003). Figure 2.10 shows an alternative path and the optimal path for a two-dimensional TSP with 19 cities. The cities are represented by the nodes and the distance between the cities by the vertices. The optimal path results in total 376 km distance while the other alternative has 540 km total covered distance.

In general, for combinatorial problems, including TSP, search algorithms (Clausen, 1999) and meta-heuristic algorithms (Dorigo & Di Caro, 1999) are often used. Finding the global optimum using these algorithms are not guaranteed and might be time-consuming in some cases. The same issues apply to the joining sequence problem. In the next section, the specific literature on the joining sequence optimization is introduced.

2.8 Joining Sequence Optimization

Joining sequence optimization strives for finding the best sequence among all the possible sequences so that a specific objective becomes optimal. Several different objectives have been considered in this optimization problem. From distortion and local shrinkage (Fukuda & Yoshikawa, 1990) to cycle time and stresses (Mochizuki et al., 2000).

The welding sequence problem is mainly studied for spot welding and continuous welding operations. Fukuda and Yasjikawa have introduced a discrete method for continuous problems, where the welding path is divided into several smaller paths. They have formulated a neural network (NN) for this problem and have shown the potential of the approach (Fukuda & Yoshikawa, 1990).

Huang et al. have applied a genetic algorithm (GA) to find the optimal sequence with the minimum displacements after spot welding (Huang et al., 1997). Several other applications have also considered the GA for this purpose (Y. G. Liao, 2005; Segeborn et al., 2011). Cycle time has also been introduced to the objective of this problem (Xie & Hsieh, 2002).

Heuristic search algorithms, such as branch and bound, have been considered to optimize the geometrical quality and the welding gun robot traveling path at the same time (Carlson et al., 2014). One issue in the formulation of the problem with the linear programming methods, specifically in branch and bound, is defining the upper and lower bounds. Generally, in point-based joining methods, after each joining step, the outcome of the assembly changes, which can have no correlation with the previous welding step. To overcome this issue, Carlson et al. have considered the outcome of the simultaneous weld as the lower bound of the problem (Carlson et al., 2014).

For defining the optimal paths of the continuous welding, with the same discrete approach as (Fukuda & Yoshikawa, 1990), surrogate models based on physical experiments and FEM simulations are built and have shown to reduce the calculation time for this purpose (Voutchkov et al., 2005).

The most widely applied optimization method for this problem has been the GA. The GA is in the category of the meta-heuristic optimization algorithms and is inspired by the natural selection (Holland et al., 1992). Applied to the sequencing problems, several other evolutionary algorithms, such as Ant Colony Optimization (ACO) (Dorigo & Di Caro, 1999), Particle Swarm Optimization (PSO) (Kennedy, 2010) have also been introduced.
The common steps in the algorithm of the evolutionary algorithms are:

1. Generate an initial random population of solutions.
2. Evaluate the fitness or cost of each solution.
3. If the ending condition not satisfied, apply the algorithm-specific operators.
4. Create new generations of the population.
5. Evaluate the fitness or cost of each solution.
6. Repeat steps 3-5 until ending condition is satisfied.

The GA specific operators are crossover and mutation. In the crossover operator, two solutions (encoded as chromosomes with genes as elements) are selected and by different strategies, for example, single-point, are swapping genes with each other. In the mutation operator, one solution is being chosen, and the genes change position within the same solution.

For applying the traditional operators to the sequencing problems, the issue of the generation of the repeated solutions and infeasible solution can occur. To avoid this type of problem, random-key encoding approach is introduced (Bean, 1994). In this approach, the solutions are encoded as real numbers between zero and 1 and after crossover, decoded back to the integer numbers representing the sequence.

Huang et al. have also introduced an approach to overcome the issues in GA for sequencing problems (Huang et al., 1997). In this approach, the redundant elements are identified, algorithmically, and swapped with feasible elements. More information on the efficient application of these methods on the sequencing problems is given in Paper 2 and 3.

One other numerical method that has been introduced to be applied to the problem is the Neural Network. In Paper 4, a Hopfield NN has been formulated to solve the contact displacement minimization problem. This type of network has shown to be effective on the combinatorial problem optimization (Salcedo-Sanz & Yao, 2004; Wang et al., 2004). The details of the applied method can be found in (Aiyer et al., 1990; Talaván & Yáñez, 2002). In paper 5, a radial basis function network has been formulated to approximate the input-output function of the sequences to the assembly response. This network is proved to be a universal approximator (Park & Sandberg, 1991); therefore, the application of this network is widespread. The details of this network can be found in (Hagan et al., 1997; Lippmann, 1989).
Going into the theory of the broad field of neural networks is outside the scope of the thesis. Therefore only the references to the theory of applied methods are provided above. The contributions of the provided theories have been limited to the application of the methods in this thesis.

Chapter 3

RESEARCH APPROACH

In this chapter, the description and justification of the research approach are presented.

3.1 Background

The focus field of this thesis is within the geometry assurance and robust design. This field can be considered as a subcategory of the design research.

As per the definition of Blessing and Chakrabarti, design is a set of activities that develops a product from a need to the full realization of it. This development is mainly done to satisfy the perceived needs (social or economic) of the users (Blessing & Chakrabarti, 2009). Using this definition of design, product development, which includes the geometry assurance area, could be merged into the design sciences. Figure 3.1 shows an integrated product and production development platform. The details of the product design, including the geometry assurance elements such as tolerances and adjusting the operation parameters virtually, are developed simultaneously as the corresponding production system is developed. In such an environment, the development of a product and the realization needs of the product are developed hand in hand.

According to Blessing and Chakrabarti, conducting research in the area of design involves the development of understanding and support. For having a more efficient and effective product, which can be defined as the goal of the design research, understanding, and providing support to that product should be tightly coupled. Figure 3.2 is a representation of the design research describing this inter-connectivity.

Different methodologies have been introduced within the design research field, out of which design research methodology (DRM) and the Hubka and Eder's scientific approach to engineering design (Hubka & Eder, 1988) have had the most applications.

Hubka and Eder have introduced a two-dimensional perspective of the design science methodology. They define design science as " *...the problem of determining*

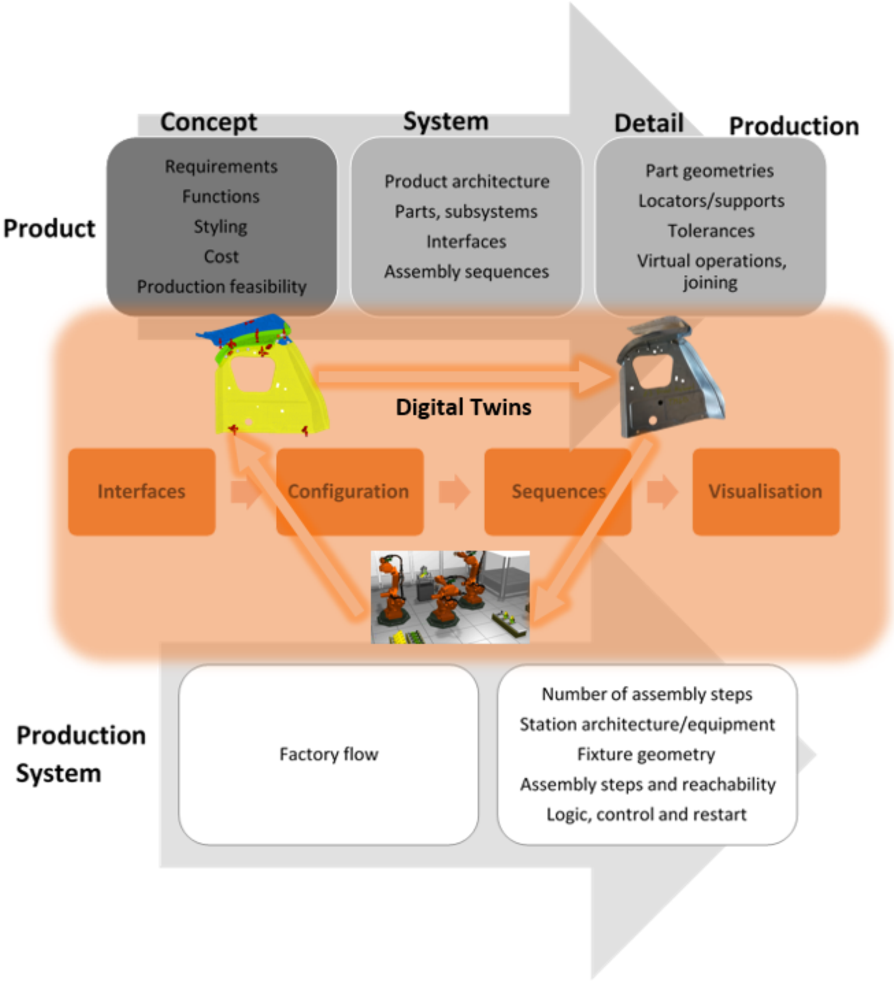


Figure 3.1: An integrated product and production development platform

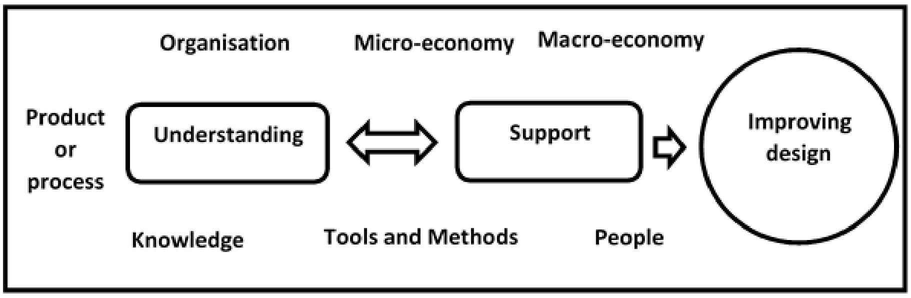


Figure 3.2: Design research: aim objectives and facets of design. The picture is inspired by (Blessing & Chakrabarti, 2009)

and categorizing all regular phenomena of the system to be designed, and of the design process. Design science is also concerned with deriving from the applied knowledge of the natural sciences appropriate information in a form suitable for the designers use".
According to Hubka and Eder, the statements within design science are descriptive or prescriptive, and the focus of them is on the technical systems or the design process (Hubka & Eder, 1988)

Although different methodologies have been introduced to be applied within the field of design engineering, following a strict set of methods linearly is not recommended. This is why the DRM states that the descriptive and prescriptive stages of design research should be used as a guide and to be followed while iterations between different stages are a necessity.

3.2 Design Research Methodology

Blessing and Chakrabarti have introduced the design research methodology in 2002. According to their definition, a methodology is defined as "*an approach and a set of supporting methods and guidelines to be used as a framework for doing design research*" (Blessing & Chakrabarti, 2009). This framework is intended to provide understanding and support to help to improve the design of research. While the design research is intended to provide understanding and support to improve the design itself. This improvement is built based on the thorough applications of different methods. The design method is defined as "*sequences of activities to be followed in order to improve particular stages of the design process (task clarification, conceptual design, detail design, etc.), and specific tasks within these stages (e.g., generation, evaluation, etc.)*" (Blessing & Chakrabarti, 2009).

Figure 3.3 is an overview of the DRM. The main stages are research clarification, descriptive study I, prescriptive study, and descriptive study II. At each stage, different methods can be used. Each stage has specific outcomes, from which different deliverables are generated.
As mentioned in the previous section, the stages of the DRM are connected and are not to be followed necessarily in one order. Different loops can be applied to different research projects. Since each design research is unique, having the possibility of going through the stages back and forth will enhance the understanding of the product or process under research.

In the research clarification stage (RC), the area of the contribution of the research will be introduced, and the measurable success criteria are being preliminary defined. In the second stage, descriptive study I (DSI), the reference model of the design is being developed.This reference model is the previously applied algorithms to the problem in the literature and industrial practice. Moreover, the key design characteristics, defining the current state, are being established. The third stage,

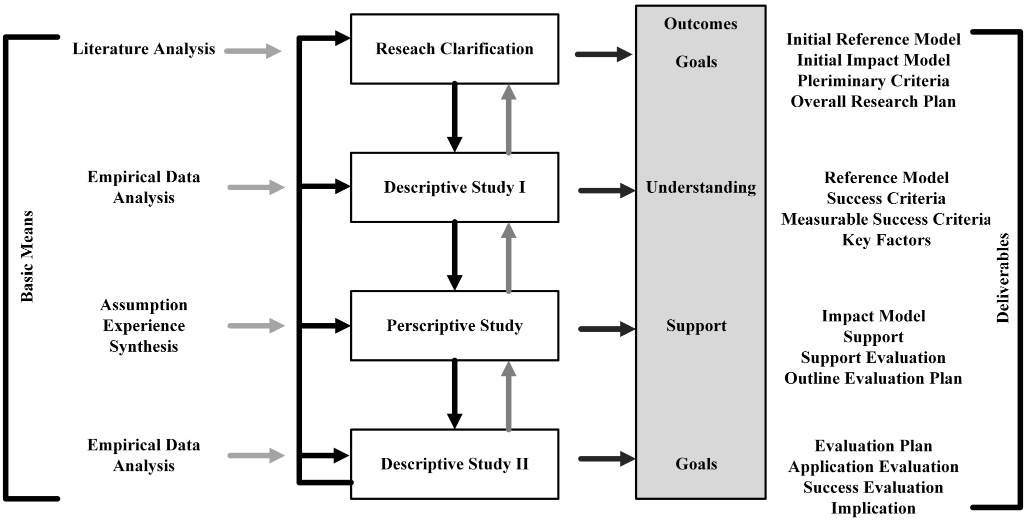


Figure 3.3: Design Research Methodology. The picture is inspired by (Blessing & Chakrabarti, 2009).

prescriptive study (PS) is where the actual support is being developed. In a design development aspect, this stage is where the actual development or improvements are introduced for making the products (or processes) more efficient. This efficiency can be evaluated using the previously defined measurable success criteria. In the descriptive study II (DSII), the impact model (the improved model) is being implemented into the process and is evaluated with regards to the success criteria.

3.3 Applied Research Methodology

In order to describe how DRM is used in this thesis, the published papers are considered as the overall results of the presented research. Therefore, the following is about the inter-connectivity of each of these publications to the different DRM stages. Moreover, how these results are connected to the individual research questions are also described.

Figure 3.4 is a schematic view of the application of DRM in this thesis. The rounded rectangles are where the comprehensive studies have been conducted, while the leaf-shapes are where review-based studies are performed in the specific stage.

The focus of this research project is on designing accurate and time-efficient algorithms to optimize the joining sequences for improved geometrical quality. The accuracy and time efficiency of the algorithm have been the success criteria of the research. Thereby, developing supports to optimize the joining sequences and also improving the existing evaluation and verification tools (compliant variation simulation) to be applied in an industrial environment is another aspect of this research.

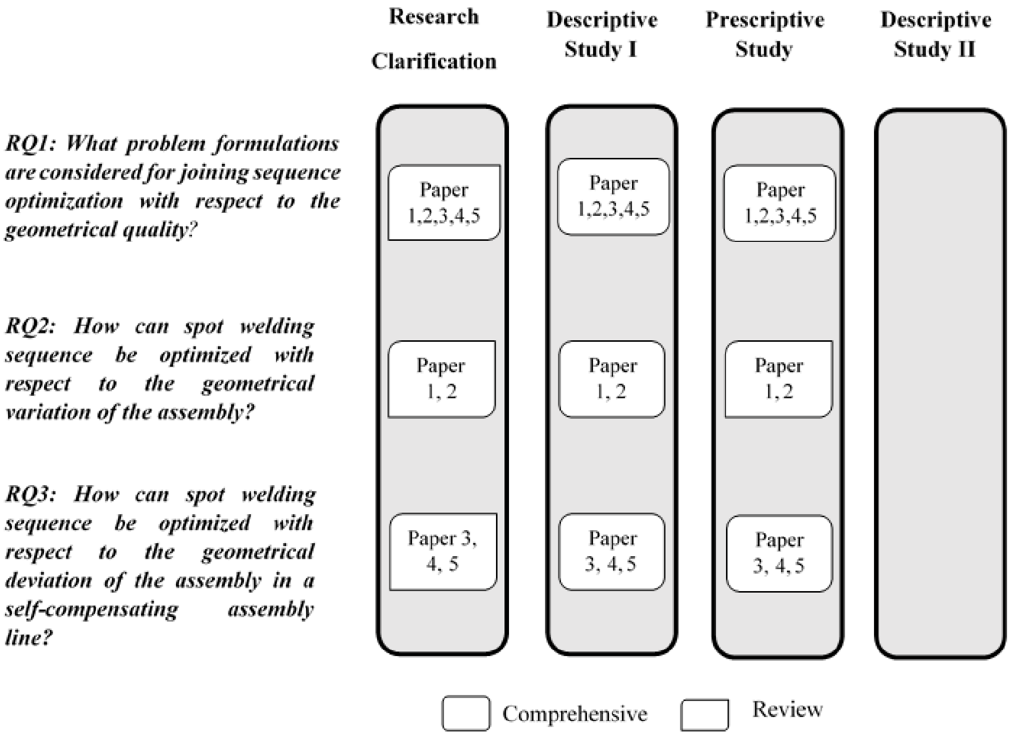


Figure 3.4: Applied Design Research Methodology

The result of this improvement will be a support for decision making during the early design and realization (production) phases. While these improvements in the evaluation tools should reduce the time required for decision making, the content of the improvement can be presented as enablers for future implementation. In case of failure in the real-time implementation of the presented improvements due to the current limitations, the results are presentable as scientific knowledge for future implementation.

3.3.1 DRM on RQ 1

The first research question, RQ 1, is about identifying the key characteristics of the formulation of the problem. The industrial perspective, together with the theoretical aspect of the problem, is sought in this question. This study will help to formulate the success criteria required to be achieved for answering RQ 2 and RQ 3. A comprehensive pre-study on the joining sequence optimization is performed, and the key process parameters are studied in the research clarification phase. The outcome of this phase can be found in all the presented papers, in the form of the review of state of the art, in the studied topic.

A field study is also conducted for understanding the industrial application of the joining process used for sheet metal assemblies in the automotive industries. A process map of the experiential approaches for identifying geometry problems in the welding process is also achieved. The outcome of this study resulted in the comparison of the simulation approaches performed in the industry in Paper 2. The theoretical approach formulating the optimization problem is also achieved from Paper 1.

Moreover, the understanding of the future implementation of the proposed support is also achieved and may be deployed in future studies.
From the extensive literature analysis and the field studies, gathering empirical data, the formulation of the joining sequence problem (initial reference model) and the need for time-efficiency (preliminary criteria) were identified.

Paper 2, evaluates the industrial approach for the formulation of the problem (the industrial reference model) descriptively. This paper also integrates the results of Paper 1, application of the evolutionary algorithms on the theoretical problem formulation (theoretical reference model) to propose a method for accurate and time-efficient optimization of the sequences, prescriptively.

Paper 3 and 4 describe the theoretical reference model and evaluates them against the success criteria. Paper 4, intends to describe both the theoretical and industrial reference model in the same formulation, understanding the root cause of the division between the reference models. The prescriptive element in Paper 1 is the application of evolutionary algorithms. In Paper 2, the reduced formulation of the problem is introduced and evaluated. Paper 3 and 4 intend to introduce an impact model, rule-based algorithms for the best outcome of the success criteria.

3.3.2 DRM on RQ 2

The second research question, RQ 2, intends to answer how the identified formulation in the reference model can be applied to propose a generic solution for a batch of assemblies.

Apart from the literature and field studies performed to answer this question in the RC stage, in the DSI phase, the reference model and the corresponding success criteria are studied. Different algorithms were studied with the current formulation of the problem, and the accuracy and time-efficiency of each were analyzed in Paper 1. Through this study, the initial understanding of the behavior of the phenomenon under study was established. The algorithms operators (the key factors) affecting the success criteria, were identified.

For optimizing the geometrical variation, the evolutionary algorithms are prescribed by Paper 1 and the reduced formulation of the problem has been introduced in Paper 2, shaping the impact model. Industrial implementation on the prototype level is within the goals of this RQ. The evaluation studies are conducted on the accuracy and efficiency of the introduced optimization algorithms on industrial assemblies, virtually.

3.3.3 DRM on RQ 3

The RQ 3 also requires the RC stage to initiate the study for retrieving an answer. This question intends to cover the main scope of the research project, in which this thesis is conducted. Descriptive studies are required to build a reference model and also prescriptive studies to provide support. Built on the literature and field studies, the RC stage, in line with the previously mentioned methods where conducted. The theory of optimization methods for the individualized assemblies is presented in Paper 4 and 5.

In the DSI phase, the reference model, the generic formulation of the optimization problem for the problem is achieved. The success criteria, which is the accuracy and time-efficiency, is common between the different studies. Identified from the answers to RQ 1, the key parameters affecting the success criteria, (initial population generation) is studied in Paper 3 and 4. Paper 5 studies how the generated reference models (theoretical optimization formulation and the reduced problem formulation) are different from each other.

New algorithms have been prescribed in Papers 3 and 4 to achieve time-efficient and accurate optimization algorithms. Building on top of all the previous papers, Paper 5 prescribes a new accurate and time-efficient method and shows the potential for future implementations.

The descriptive study II stage requires to integrate the presented optimization methods, impact models, into a geometry assurance digital twin. The methods have to be evaluated in a physical setup where the twin steers the self-compensating assembly line. This stage of the DRM may be addressed in the future, where the implication of the outcome of the physical applications of this concept is achieved.

3.4 Methods

As defined before, the methodology is looked upon as a logic, connecting all the methods. In other words, it can be defined as a framework of the including methods and research elements. In this section, the used methods in the applied DRM is introduced. The connection to the methodology can be made simply through Figure 3.4 presented in the previous section.

3.4.1 Literature studies

An imperative part of the research is developing understanding of the phenomenon under study. In this research, the part of the understanding is achieved in all the phases through extensive literature studies. All the papers are taking advantage of this method for introducing the applied tools and further describing the different approaches in the previous research.

3.4.2 Field studies

Field studies is a method for data collection. In this method, the phenomenon is studied by direct or indirect observation or interviews. The gathered data is in the form of notes, videos, or images (Karlsson, 2010). As mentioned in the previous section, this method is used mainly in the research clarification stage. Automotive industry in Sweden and Japan have been studied. Sheet metal forming factories have been observed and interviewed. Understanding with respect to sheet metal joining physical parameters and needs have been achieved. The information regarding the industrial sheet metal assembly simulation approaches have been gathered. Industry best practice approaches in the form of tacit manufacturing knowledge, for spot weld sequencing have been studied in Papers 2 and 3.

3.4.3 Hypothetico-deductive method

The Hypotetico-deductive method has been considered to guide scientific research (Lawson, 2000). According to Lawson, the method consists of six fundamental elements.

- Raising questions.
- Generating hypothesis.
- Assuming that the hypothesis is correct.
- Using the process of deduction (if,. . . , and. . . , then, . . .) to generate the expected results.
- Conduct tests and gather evidence.
- Conclude

The general hypotheses in the presented papers are: Paper 2 expects to retrieve accurate results by reducing the optimization problem while time is being saved.
Paper 3 states that if the complete optimization problem is formulated with evolutionary algorithms, then the manufacturing knowledge about the assembly can help to initiate the algorithms to achieve accurate results time-efficiently.
Paper 4 suggests that the rules can be generated quantitatively by numerical simulations, not only qualitative data.
Paper 5 proposes that in every assembly, a small fraction of the complete sequence have significant contribution to the geometrical quality of the assembly. Therefore the sequence of these points should be considered in the sequence analysis.

3.4.4 Experiment

In accordance with the description of the previous method, experimenting is part of proving that a hypothesis is accepted or not.
Experiments have been used using numerical simulation to evaluate the generated

hypotheses in the Papers 2,3,4,5.

Design of experiments, a screening method, is used in Paper 1 for exploring the identified algorithm parameters.

Chapter 4

RESULTS

This chapter presents a summary of the results presented in the appended papers.

4.1 Paper 1 - Joining Sequence Optimization by Evolutionary Algorithms

Spot welding sequence has shown to have a considerable impact on the final geometrical outcome (Fukuda & Yoshikawa, 1990; Segeborn et al., 2011; Xie & Hsieh, 2002). For solving this problem, previous studies have been focusing on the Genetic algorithm, while several other evolutionary-based algorithms have shown to perform faster for combinatorial problems.

To investigate the applicability of other evolutionary optimization algorithms on the problem, and to compare their performance, the well-known Ant Colony Optimization (ACO), which have shown to be efficient for the combinatorial problem (Dorigo & Gambardella, 1997) has been chosen. Moreover, the competitor of the GA for the continuous problems, and also combinatorial problems (Y.-F. Liao et al., 2012), Particle Swarm Optimization (PSO) is selected for evaluation and comparison to GA on spot welding sequence optimization with respect to geometrical quality.

In order to apply the algorithms to the problem, the simulation-based optimization method is proposed for real-time applications. Figure 4.1 presents the basic idea of this method, in which the variation simulation tool is connected to the optimization algorithm as the cost function to evaluate the geometrical variation of the assembly after each sequence.

Using this method, the three mentioned algorithms, GA, ACO, and PSO are applied to the selected method. The overview of the algorithm steps is presented in Figure 4.2.

As a measure of the geometrical variation of the assembly, the Root Mean Square (RMS) of the variation (6σ) of all the nodes in the normal direction is considered for evaluation. This measure is chosen for its generic formulation of representing the total assembly variation. The optimization approach is independent of the specified

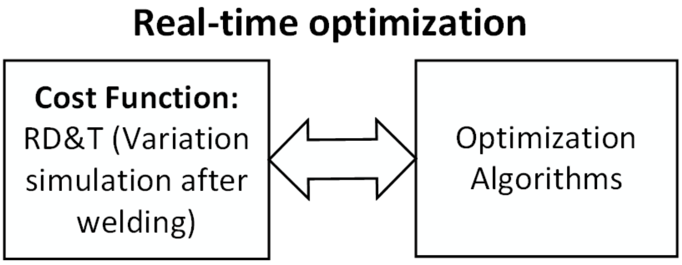
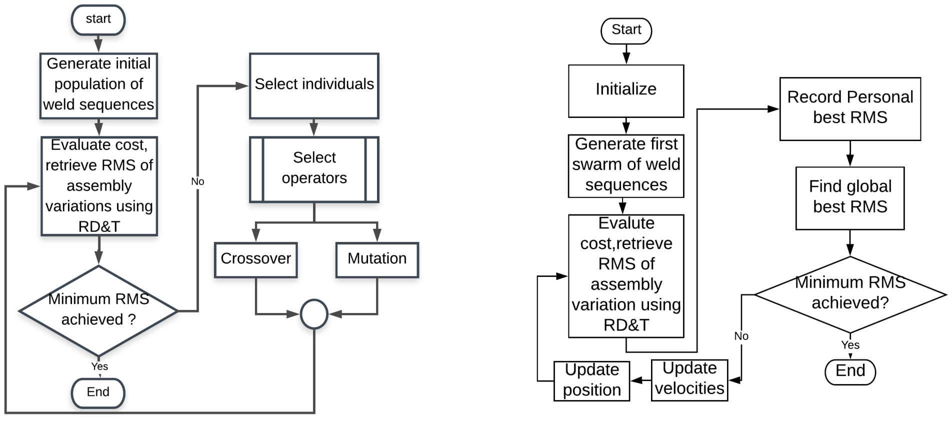
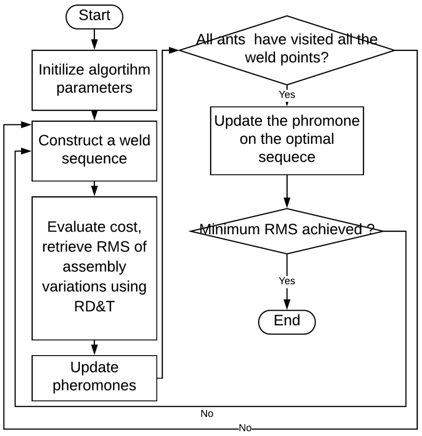


Figure 4.1: Optimization method using variation simulation (Tabar et al., 2018)



(a) Applied GA

(b) Applied PSO



(c) Applied ACO

Figure 4.2: The applied optimization algorithms (Tabar et al., 2018)

quality measure. This measure can be changed to any other critical measure on the assembly.

The proposed optimization method is applied to three automotive sheet metal assemblies, and the performance of the three algorithms are reported in 100 trials. This means that the algorithms have been run 100 times to achieve the ending condition. The measure for the performance of the algorithm has been the number of cost function evaluations (NFE). In other words, for every time that the algorithms call the variation simulation tool to evaluate a sequence, one instance is added to the NFE. Besides, the mean RMS that is achieved in the 100 trails is reported. Achieving the global optimum is essential for complete reduction of the effect of inefficient sequencing. Exhaustive searches have been performed on all the assemblies, and the global optimum for each assembly is identified. The ending condition for the algorithms has been set to reach the convergence in less or equal to 100 iterations.

Based on the results achieved, the ACO performed faster, with at least 35% less NFE, compared to the other two algorithms in two cases with neglectable errors from the global optimum. The GA performed faster in one assembly, with 35% less NFE compared to ACO. When it comes to the occurrence of the optimum in 100 trials, the PSO algorithms was more effective with 65, 91, and 99 % for reference cases 1 to 3, respectively.
Based on the results, it is realized that ACO and PSO can perform faster and more accurate compared to the previously applied GA, depending on the assembly complexity. It is concluded that the advantages of the stand-alone algorithms compared to each other are not sufficient for real-time applications in a digital twin. The stand-alone algorithms are highly dependent on the quality of the randomly generated initial population. It is suggested that biased initial values are introduced to the models for the initial population, and parallel computing to be performed to real-time applications.

4.2 Paper 2 - Identification of the Geometry Joints

Joining sequence optimization is a computationally heavy task. Previous studies have considered solving the complete sequence problem. In the automotive industry, the joining operation is divided into two steps, the geometry cell, and the re-spot cell. The points that are most critical for the geometrical outcome of the assembly are being welded first in the geometry cell. The selection of the geometry weld points has not been addressed in the relevant literature. Through the introduction of the methods for the geometry weld point selection, a reduced sequencing problem is achieved, and a significant amount of time to optimize the sequence of the weld point can be reduced. Three strategies for choosing geometry points have been introduced and used to reduce the optimization problem size.

Figure 4.3 presents the proposed evaluation and optimization approach. Initially, the geometry weld points are being selected with the support of the three proposed

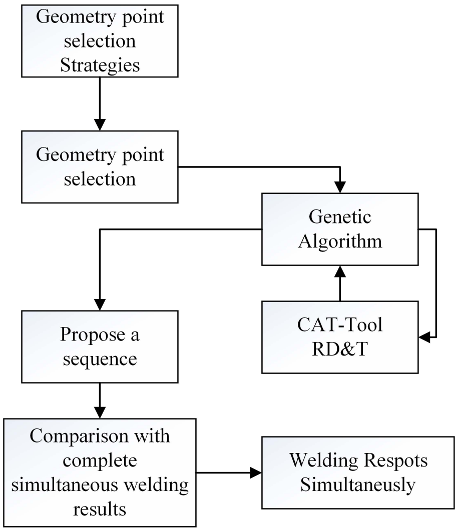


Figure 4.3: The proposed optimization and evaluation method (Tabar et al., 2019a)

selection methods; the sequence of theses points are optimized. The sequence of the rest of the weld points can be set in any arbitrary sequence. In this case, simultaneous welding simulation has been considered for the rest of the points.

Three strategies for geometry weld point selection are presented for integration into the above method:

- Distance to positioning system
- Weld gap
- Weld point relative sensitivity

The details of the presented method can be found in Paper 2. The optimization problem is formulated for finding the optimal sequence of the geometry points with respect to RMS of the 6σ variation of all the nodes in the assembly. GA is considered for integration in the proposed method, while any other evolutionary algorithm can also be used.
The method has been applied to three automotive sheet metal assemblies, and the mean NFE and RMS are reported in 1000 trials. The results are also compared with simultaneous welding, and the time comparison is made between a GA on the complete problem and the reduced problem.

Figure 4.4 shows the application of the proposed method on the three assemblies. The method shows that selection of the geometry points based on the relative sensitivity of the weld points is consistent with 3.45% to 10.89% impact from the re-spots and also the lowest error compared to simultaneous welding results.
The time comparison performed also shows that with the presented method, with the relative sensitivity geometry weld point selection, 36% to 93% of the NFE required

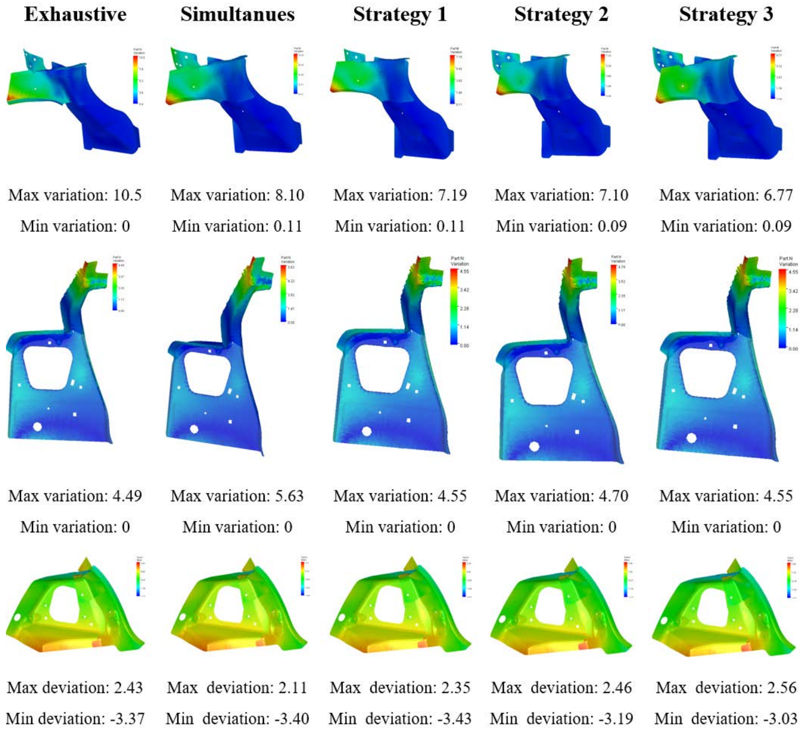


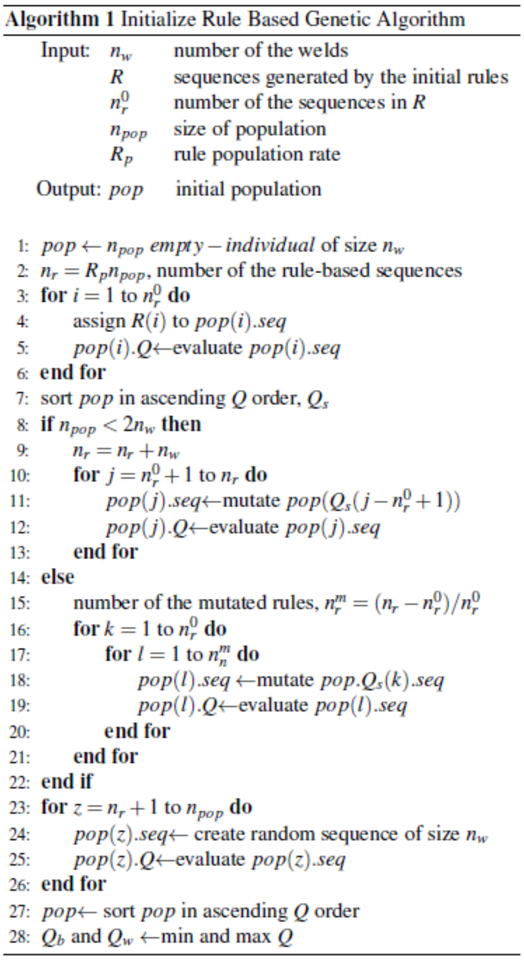
Figure 4.4: The proposed method applied on three assemblies (Tabar et al., 2019a)

to optimize the complete problem can be saved.

Based on the results achieved, it is suggested that the approach of geometry point selection is efficient, both in time and accuracy aspects. Generic and numerical approaches to select geometry weld points can help to reduce the problem size and help to reduce the calculation complexity of the joining sequence optimization.

4.3 Paper 3 - A Rule-Based Method for Joining Sequence Optimization

Spot welding sequence optimization using the MIC method together with the EAs is time-consuming. Previous research has optimized the sequence, not considering the time aspect. Therefore, a consensus on the GA can be seen in the previous and more recent studies (Bean, 1994; Huang et al., 1997; Y. G. Liao, 2005; Segeborn et al., 2011; Xie & Hsieh, 2002). All of the mentioned studies have considered stand-alone GA, where the initial population is generated by random initiation of feasible sequences. This aspect per se increases the NFE and consequently, the optimization time. Rules and strategies for selection of the weld points have also been studied individually. In this study, these two approaches have been combined to propose a rule-based algorithm for time efficient spot welding sequence optimization for each individual assembly. Three generic rules for assigning the initial population of the EAs have been introduced as follows:



```
Algorithm 1 Initialize Rule Based Genetic Algorithm
  Input:  $n_w$          number of the welds
          $R$            sequences generated by the initial rules
          $n_r^0$        number of the sequences in $R$
          $n_{pop}$      size of population
          $R_p$          rule population rate
  Output: $pop$          initial population

$pop \leftarrow n_{pop}$ $empty-individual$ of size $n_w$
$n_r = R_p n_{pop}$, number of the rule-based sequences
for $i = 1$ to $n_r^0$ do
    assign $R(i)$ to $pop(i).seq$
    $pop(i).Q \leftarrow$evaluate $pop(i).seq$
end for
sort $pop$ in ascending $Q$ order, $Q_s$
if $n_{pop} < 2n_w$ then
    $n_r = n_r + n_w$
    for $j = n_r^0 + 1$ to $n_r$ do
        $pop(j).seq \leftarrow$mutate $pop(Q_s(j - n_r^0 + 1))$
        $pop(j).Q \leftarrow$evaluate $pop(j).seq$
    end for
else
    number of the mutated rules, $n_r^m = (n_r - n_r^0)/n_r^0$
    for $k = 1$ to $n_r^0$ do
        for $l = 1$ to $n_n^m$ do
            $pop(l).seq \leftarrow$mutate $pop.Q_s(k).seq$
            $pop(l).Q \leftarrow$evaluate $pop(l).seq$
        end for
    end for
end if
for $z = n_r + 1$ to $n_{pop}$ do
    $pop(z).seq \leftarrow$ create random sequence of size $n_w$
    $pop(z).Q \leftarrow$evaluate $pop(z).seq$
end for
$pop \leftarrow$ sort $pop$ in ascending $Q$ order
$Q_b$ and $Q_w$ $\leftarrow$min and max $Q$
```

Figure 4.5: The proposed initialization algorithm (Tabar et al., 2019c)

- Distance to positioning system
- Initial weld gap
- Recursive weld gap. In this approach the initial weld gaps are evaluated and one weld point is being selected. The selected weld points are welded recursively and the weld gaps are evaluated.

The details of each rule are presented in Paper 3. Using the presented rules, the EAs can be initiated. Due to the generality and the previous applications of the GA, this algorithm has been considered for implementation of the presented rules. Figure 4.5 is the proposed algorithm for the initialization of the GA. The sequences derived from the rules are assigned to the initial generation, according to the population size. For larger populations sizes than the number of the rules, the mutations of the best rule are considered for the initialization. If the population size is less than the assigned rules, then this is compensated by adding the required solutions to the initial population.

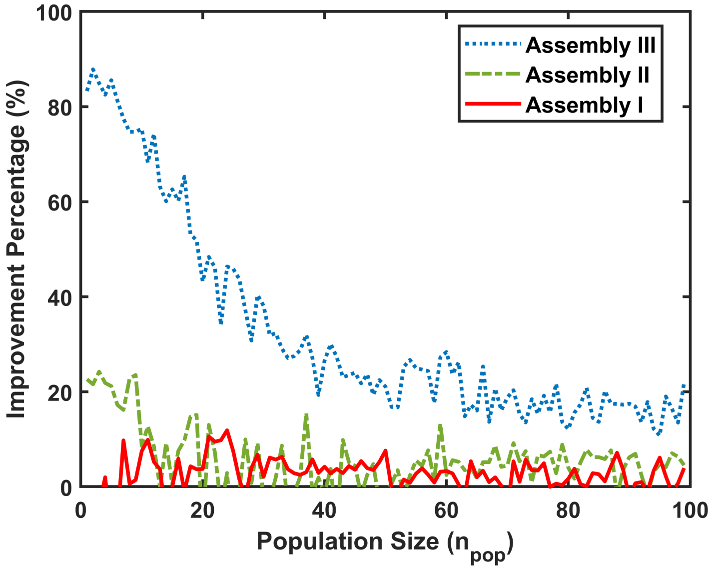


Figure 4.6: The improvement achieved applying RBGA compared to GA (Tabar et al., 2019c)

The rule-based genetic algorithm (RBGA) is applied on three automotive sheet metal assemblies, and a time comparison has been made with a stand alone GA. Population sizes 2-100 have been tested, where for each population, 1000 trials have been performed. The improvement that was achieved by the RBGA compared to the stand-alone GA on the three assemblies are shown in Figure 4.6. In most of the population sizes, the RBGA has performed faster to reach the global optimum. In the population sizes 10 to 11, a considerable improvement of 10 to 80 percent is achieved.

The study has shown that applying suitable rules to the evolutionary algorithms helps to improve the efficiency of the algorithms with regards to the number of evaluations required to converge to the global optimum. In other words, less optimization time is needed. It is suggested that a parallel rule-based algorithm is implemented in the concept of the self-compensating assembly line, presented in (Söderberg et al., 2017), for further time reduction.

4.4 Paper 4 - Minimized Contact Displacements for Joining Sequence Optimization

Spot welding sequence optimization using the stand-alone GA is a time-consuming task. Rule-based approaches have shown to reduce the computation time, by introducing knowledge about the assembly to the optimization. The introduced RBGA have shown to improve computation time. The rules in the RBGA are based on best practice approaches and the model sensitivity to the weld gaps. As previously mentioned in Section 2.6, the contact modeling in the compliant variation simulation imposes non-linear behavior to the assembly response to disturbances. In this study, an approach for spot welding sequence optimization based on the minimized contact displacements are introduced to reduce the computation time compared to the stand-alone GA.

The summary of the proposed method is as follows (Tabar et al., 2019d):

1. Propose sequences corresponding to the minimized contact displacements using the Hopfield network method.
2. Evaluate the proposed sequences.
3. Choose the sequence with minimum assembly displacements.
4. Apply the proposed modified GA to retrieve the optimal sequence.

The proposed method formulates the contact displacement problem after each welding step, using a Hopfield network approach. The sequences achieved in this step are used as the initial population in a modified GA, where generations are built based on the mutation of the best sequences.

The proposed method has been applied on two reference assemblies and the computation time has been compared to a stand-alone GA. The method results in 60-80 % improvement in the computation time in 100 trials. It is suggested that this approach is combined with the previous RBGA to further increase the efficiency of the algorithms. It is also suggested that surrogate models are developed based on the proposed MCD approach and parallel computation to minimize the computation time required for this purpose.

4.5 Paper 5- A Surrogate-Assisted Optimization Approach

Spot welding sequence optimization belongs to the category of combinatorial problems, where for each sequence non-rigid variation simulation is required, to achieve the minimum assembly deviation. Standard GA has been applied to the problem in previous research (Huang et al., 1997; Segeborn et al., 2011; Tabar et al., 2018). Rule-based algorithms and minimized contact displacement approach have been introduced, in this thesis, to increase the efficiency of the algorithm (Tabar et al., 2019c, 2019d). Moreover, reducing the problem size by selecting the geometry weld points have shown to be an effective method for this purpose (Tabar et al., 2019a). In this work, an effective approach to map the function of the sequence input and the assembly deviation output is presented. Based on the presented approach, the function is approximated, and a surrogate model is built to retrieve the assembly deviation of each sequence. The time comparison between the presented method and the standard GA is presented.

The outline of the proposed method is as follows (Tabar et al., 2019b):

1. Generate a sample using the provided sampling strategy, $\binom{N_w}{s} s\,!$, (N_w is the number of the welds in the assembly and s is the number of the sampled welds).
2. Evaluate the sample in parallel based on the available evaluators.
3. Approximate the input-output function using an RBF network, and build a surrogate model
4. Evaluate all the sequences using the surrogate model.
5. Retrieve the sequence corresponding to the minimum geometrical deviation
6. Evaluate the proposed sequence, numerically, to verify the outcome.

The method has been applied to three automotive sheet metal assemblies, and time comparison has been performed to the GA.

The results show that the proposed surrogate assisted approach is capable of providing sequences with marginal errors from the global optimum. For time comparison, the surrogate-assisted method is in advantage, compared to the GA, due to the ability to parallelize the method. It has been shown through the application of the proposed method, depending on the number of evaluators used, 0-91 % time improvement can be achieved compared to a standard GA.
The method has established a niche for future studies on the selection of the geometry weld points based on the numerical simulations, time-efficiently.

Chapter 5

DISCUSSION

In this chapter, the answer to the research questions, based on the presented results and the appended papers are given. The scientific and industrial contribution of the presented research is presented. The validation and verification discussion is also provided.

5.1 Answers to the Research Questions

RQ1: What problem formulations are considered for joining sequence optimization with respect to the geometrical quality?

Geometry dependent rule-based approaches for spot welding sequencing have been studied in the previous research. Examples of these approaches are direction based approaches such as left to right, middle and outwards. In this type of formulation, extensive experiments and manufacturing knowledge is needed for sequencing of one individual assembly.

Other studies have considered complete sequence optimization with regards to geometrical variation and deviation, using search methods or evolutionary algorithms. Based on the presented results, two primary formulations for the problem are proposed.

1. Complete sequence formulation with regards to geometrical variation and deviation:
   Paper 1 shows that optimization of the complete sequence with regards to geometrical variation presents a single sequence for a batch of assemblies. This sequence consists of all the weld points in the assembly. The advantage in this formulation is that minimum process adjustment are required to achieve an improved quality of a batch. However, the sequence does not guarantee to result in the minimum deviation of each individual assembly.
   Papers 3 and 4 show that optimization of the complete sequence with regards to the geometrical deviation provides a single sequence for each assembly while

all the weld points are being evaluated.

2. Partial sequence problem with regards to geometrical variation and deviation: Paper 2 shows that optimization of the partial sequences for geometrical variation considers choosing a number of the most important weld points based on the geometrical quality criteria, and considers optimization of the partial permutations of all the weld points in the assembly.
   Paper 5 presents that partial sequences can be selected for optimization of the sequences with regards to geometrical deviation, by the surrogate assisted method presented.

RQ2: How can spot welding sequence be optimized with respect to the geometrical variation of the assembly?

1. Paper 1 shows that by utilizing the evolutionary algorithms, an improved sequence can be suggested to decrease the total geometrical variation of the batch of assemblies. While different optimization algorithms can be applied to retrieve an optimized sequence, the evolutionary algorithms have shown to produce the near-optimal solutions in a shorter time compared to the linear programming algorithms. Complete sequence optimization is achieved by the evolutionary algorithm efficiently with respect to time. However, achieving the exact solution to the problem is not guaranteed.

2. Partial sequence problem formulation is achieved by the proposed clustering methods in Paper 2, from which considering the sensitivity of the weld points have shown to be consistent. Three rules are proposed for the selection of the geometry weld points, and the sequence of these points can be optimized using the evolutionary algorithms. Moreover, the partial sequences can be selected by the sampling strategy that is presented in the Paper 5, where the sequence of the initial weld points are considered for sequence evaluation. This is achieved by the accurate sampling strategy presented in the Paper 5, and building a surrogate-assisted approach to find the optimal sequence for the minimum geometrical deviation.

RQ3: How can spot welding sequence be optimized with respect to the geometrical deviation of the assembly in a self-compensating assembly line?

1. In this formulation, several sequences are needed to be generated based on the selected instances of the parts in the assembly. If there are 25 assemblies to be built 25 sequences need to be proposed for each assembly, which corresponds to the optimal geometrical outcome for each instance.
   Paper 3 presents a new rule-based genetic algorithm which can provide the optimal sequence efficiently in time. This approach is further enhanced by

introducing a method to solve partial sequences with a contact displacement minimization. Paper 5 presents a novel surrogate-assisted approach to propose a sequence with respect to the minimum geometrical deviation of the assembly. The approach has shown to be fully parallelizable and accurate, saving considerable amount of time and while having marginal errors from the global optimum.

2. Paper 5 also unveils the potential of the proposed surrogate-assisted approach for identifying the initial sequences, to be considered for partial sequence evaluation. The approach proposes the partial sequences from the complete optimal sequence.

5.2 Research Contribution

The presented research holds both scientific and industrial relevance. These two aspects are discussed below.

5.2.1 Scientific contribution

The scientific contribution of the thesis, in a nutshell, involves increased knowledge about the joining sequence parameter and its effect on the geometrical outcome and computational efficiency to find an optimal solution.
To achieve the contributed knowledge, the following aspects are considered:

- Evaluation of different optimization algorithms on the joining sequence problem has been presented.

- A new formulation for achieving a reduced problem size has been proposed, identifying the geometry joints, through the three proposed strategies.

- A new rule-based algorithm has been proposed increasing the efficiency of the evolutionary algorithms.

- The proposed rule-based algorithm is further improved by introducing rules generated based on the numerical formulation of the problem.

- A novel surrogate-assisted approach has been introduced for increased calculation time efficiency compared to the rule-based algorithms. The method is intended to identify the geometry weld points, numerically.

5.2.2 Industrial contribution

The industrial contribution of the thesis corresponds to the application of the proposed scientific methods into the product development cycle of any industry dealing with point-based joining. This proposed method can be implemented in two different perspectives:

- Proposing a sequence of welding to improve the process in the assembly cells. This is achieved by prior optimization of the weld points with respect to the geometrical accuracy, in the design phase.

- Proposing individualized sequences for each assembly in the concept of the self-compensating assembly line, or the geometry assurance digital twin. The proposed scientific approaches help to integrate this parameter to the digital twin concept for further implementation to increase the geometrical quality.

5.3 Verification and Validation

The presented thesis is based on the research conducted in the first three stages of the DRM, clarification, descriptive, and prescriptive studies. These three stages aim to build knowledge and understanding around the phenomenon under study and to propose a support for the problem of the study.

To discuss the validation and verification aspects, the definition of each, in this thesis, are given. According to Boehm, verification of a product involves with process of determining if the product satisfies the requirements. While validation, is the process of ensuring the compliance of the product with the requirement (Boehm, 1984). In simple words, this statement can be translated into, verification; if the product is being built right, and validation; if the right product is being built.

To verify if the methods are proposed in the right way, *logical verification* or *verification by acceptance* are followed (Buur & Andreasen, 1990). *Logical verification* entails consistent, coherent, and complete research elements. Consistency is achieved when there is no conflicts between individual axioms of the research theory. Coherency is the agreement of the established methods and the theories. Completeness is achieved when all relevant observations or findings can be discussed by the established theories.
There are no conflicts observed in the established methods in this research. The consistency of the research, is verified by consistently crosschecking that no conflictive results are obtained. The coherency of the established methods is verified by constructing each element from the previously applied research within the scope of the thesis. The completeness of the research elements is verified by following the guidelines of the applied research methodology. However the complete application of the proposed methods is realized in the second descriptive study of the methodology, where the the methods, within the self-compensating assembly cells are implemented

in a physical setup.
Verification by acceptance involves the process of accepting the presented research by the experts within the field of the subject. By the definition of the validation provided, this aspect can be interpreted as a validation process over the verified research elements. In this thesis, the results are presented in the form of scientific papers. The process of publishing the results for the scientific community through this medium requires peer-review of the experienced fellows and acceptance of the presented research. Moreover, the industrial application of the presented method requires acceptance of the presented method by the industrial community. The presented research is conducted in close collaboration with industry, ensuring the acceptance of the results.

The validity of the research conducted can be discussed in three different aspects, internal, external, and construct validity (Winter, 2000).

- Internal validity: Concerns the validity of the results within the study, i.e., identifying if the meaningful causes of the outcome are studied. This aspect was insured in the studies by performing numerical simulation and experiments analyzing the involved parameters in the model. Statistical methods have been implemented in the studies, analyzing the mean and variance of the achieved results. For statistical significance, the simulations have been performed with more than 100 trials in all the studies.
  As Sargent categorizes, graphical representations of the results, *animations*, and *operational graphics*, are techniques utilized for validation of the simulation models (Sargent, 2010). Using the CAT tools, the variation propagation, stochastic results, are visualized for further validation of the results. *Degenerate tests* (Sargent, 2010) have been performed in Paper 1, identifying the algorithm behavior and the right choice of the parameters.

- External validity: Concerns the generalizability of the results outside the environment of the study. The studies have been designed for analyzing the sequence of the joints. In all the studies, the spot welding process is modeled while the joints have been completely functional. With this assumption it can be claimed that any other point-based joint, locking all the degrees of freedom in the point, could be analyzed with the proposed formulation.
  Comparison to other models is another validity technique (Sargent, 2010). The results in all the studies have been compared with different models to ensure the generalizability of the results to other assemblies of with other parameters.

- Construct validity: Concerns the validity of the study measuring the claimed outcomes. In other words, construct validity measures the appropriateness of the inferences made based on the studies performed. The studies in Papers 3-4-5 intend to increase the efficiency of the optimization methods while being accurate. Exhaustive searches have been performed on all the test assemblies, and it has been ensured that the global optimum is achieved, while the optimization time is reduced. As Sargent defines, for simulation validation, *face validity* is when the experts about the system are asked for reasonable outcomes. The simulation outcomes have been consulted with industrial partners, knowledgeable in the assembly process of sheet metals. In addition, the simulation results, using the variation simulation, have been compared with the inspection point measurements in (Wärmefjord et al., 2010), constructing *historical data validation* (Sargent, 2010).

Chapter 6

CONCLUSION

In this section, the conclusions are drawn based on the analysis of the presented results of the research. Future research plans are also presented.

6.1 Conclusions

To ensure the future competitiveness of the manufacturing industry and to reach the sustainability goals, optimization and simulation-based approaches are becoming prominent. With the recent breakthroughs in the digitalization arena and the availability of big data in the vision of the cyber-physical manufacturing systems, the concept of the geometry assurance digital twin and self-compensating assembly line have been introduced. Real-time optimization of the assembly parameters for individualized assemblies is in the scope of this concept.

Joining sequence has shown to have a significant impact on the geometrical outcome of the assembly. This parameter has been considered as a noise factor in the robust design process, specifically in industry. Little research is performed on optimization of the sequence of the point-based joints. The computational expenses of the proposed approaches have been infeasible for real-time applications. In this thesis, a detailed explanation of the applied formulations on the joining sequence optimization is provided. Two formulation approaches have been proposed and discussed in the presented results, complete sequence, and reduced optimization problem. Based on the presented results, it can be concluded that:

- Standard evolutionary and search algorithms are mainly applied in the previous research, without consideration of the computation time aspect, which makes the methods heavily time-dependent.

- Reduced formulation of the spot welding sequence, through efficient geometry point selection, can help to improve the geometrical quality, while a considerable amount of computation time is being saved.

- The rule-based approaches, RBGA and MCD reduce the computational heaviness of the evolutionary algorithms, to ensure that the optimal sequence is achieved and no more improvements can be achieved by adjusting the sequences.
- The issue with the evolutionary and search algorithms is their low ability for parallel computations. The new solutions are dependent on the evaluations of the previous solutions. To be able to parallelize the process, the surrogate-assisted approach, together with the proposed sampling strategy, is introduced. The approach is fully parallelizable; by increasing the number of evaluators, the computational time will be reduced drastically.
- The surrogate-assisted approach shows the potential for identification of the geometry weld points numerically, to be used for assembly planning and sequencing.

6.2 Future Research

The future research, based on the presented findings and the scope of the research project, includes:

- Proposing an efficient parallelizable search algorithm for joining sequence optimization of the complete sequence, and proposing the geometry weld points, to be considered for assembly planning, simultaneously. These algorithms take advantage of the findings in Paper 5.
- Application of the proposed method for other assembly steps like clamping sequences.
- A framework for optimization of the other joining parameters such as number and position.
- An optimization framework based on the sensitivity ranks of the assembly to different assembly parameters.

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