THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

INDIVIDUALIZING ASSEMBLY PROCESSES FOR GEOMETRIC QUALITY IMPROVEMENT

ABOLFAZL REZAEI ADERIANI

CHALMERS

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
GOTHENBURG, SWEDEN 2021

Individualizing assembly processes for geometric quality improvement

ABOLFAZL REZAEI ADERIANI
ISBN 978-91-7905-444-1

Doctoral thesis at Chalmers University of Technology
New serial no. 4911
ISSN 0346-718X

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

Cover: The assemblies seem to be the same, but each assembly has its unique geometry and properties that scanning technologies can reveal. These data can be utilized to treat each assembly individually to maximize the quality.

Printed in Sweden by
Chalmers Reproservice
Gothenburg, 2021

Abstract

Dimensional deviations are a consequence of the mass production of parts. These deviations can be controlled by tightening production tolerances. However, this solution is not always desired because it usually increases production costs. The availability of massive amounts of data about products and automatized production has opened new opportunities to improve products' geometrical quality by individualizing the assembly process. This individualization can be conducted through several techniques, including selective assembly, locator adjustments, weld sequence optimization, and clamping sequence optimization in a smart assembly line for spot-welded sheet metal assemblies.

This study focuses on two techniques of individualizing the assembly process, selective assembly, and individualized locator adjustments in assembly fixtures. The existing studies and applications of these methods are reviewed, and the research gaps are defined.

The previous applications of selective assembly are limited to linear and rigid assemblies. This study develops the application of selective assembly for sheet metal assemblies. This research addresses another research gap regarding the selective assembly of sheet metals by reducing the calculation cost associated with this technique.

This study also develops a new locator adjustment method. This method utilizes scanned geometries of mating parts to predict the required adjustments. Afterward, a method for individualized adjustments is also developed. Considering applied and residual stresses during the assembly process as constraints is another contribution of this research to locator adjustments. These methods are applied to three industrial sample cases and the results evaluated. The results illustrate that individualization in locator adjustments can increase geometrical quality improvements three to four times.

Accumulation of the potential improvements from both techniques in a smart assembly line is also evaluated in this study. The results indicate that combining the techniques may not increase the geometrical quality significantly relative to using only individualized locator adjustments.

A crucial factor in the achievable improvements through individualization is the utilized assembly fixture layout. This study develops a method of designing the optimal fixture layout for sheet metal assemblies. Different design and production strategies are investigated to acquire the maximum potential for geometrical improvements through individualization in self-adjusting smart assembly lines.

Keywords: Selective Assembly, Locator Adjustments, Individualization of production, sheet metal assembly processes, Geometry Assurance, Variation Simulations.

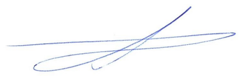
Acknowledgments

This study has carried out in collaboration within Wingquist Laboratory and the Area of Advance Production at Chalmers within the Smart Assembly 4.0 project, financed by the Swedish Foundation for Strategic Research. Their support is gratefully acknowledged.

I would like to thank my supervisor, Professor Kristina Wärmefjord for helping me in every step of the work. It would not have been possible for me to perform this work without her patient and kind guidance. I would like to thank my examiner and co-supervisor, Professor Rikard Söderberg who guided the research through his great knowledge and experience in the field. Further, I wish to express my deepest gratitude to my second co-supervisor, Associate Professor Lars Lindkvist, by helping me understand and implement variation simulations at every stage of my work.

I would like to acknowledge the help that I received from the experts in Volvo Cars Company, particularly from Björn Lindau by providing technical and practical comments on my work.

Finally, my special thanks to my friends, colleagues, my mother Soghra and my girlfriend Ghazal who helped me work in a friendly environment and enjoy being a researcher.



Abolfazl Rezaei Aderiani
Gothenburg, Sweden, February 16, 2021

Publications

The following publications are appended to this thesis:

Paper A

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., (2019), "Developing a selective assembly technique for sheet metal assemblies", *International Journal of Production Research*, 57(22): 7174-7188.

Paper B

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2020), "An Improved Phenotype-Genotype Mapping for Solving Selective Assembly Problem Using Evolutionary Optimization Algorithms", *ASME Journal of Computing and Information Science in Engineering*, 20(6): 061010-061018.

Paper C

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., (2019), "Individualizing Locator Adjustments of Assembly Fixtures Using a Digital Twin", *ASME Journal of Computing and Information Science in Engineering*, 19(4): 041019-041028.

Paper D

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2020), "Combining Selective Assembly and Individualized Locator Adjustments Techniques in a Smart Assembly Line", *Procedia CIRP*, 97: 429-434.

Paper E

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., Lindau, B. (2020), "Optimal Design of Fixture Layouts for Compliant Sheet Metal Assemblies", *International Journal of Advanced Manufacturing Technology*, 110: 2181–2201.

Paper F

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2021), "Evaluating Different Strategies to Achieve the Highest Geometric Quality in Self-adjusting Smart Assembly Lines", *Journal of Robotics and Computer-Integrated Manufacturing*, *Revised*.

Additional publications

Rezaei Aderiani, A., Wärmefjord, K., and Söderberg, R., (2018), “A Multistage Approach to the Selective Assembly of Components Without Dimensional Distribution Assumptions”, *Journal of Manufacturing Science and Engineering*, 140(7): 071015-071023.

Cronrath, C., Aderiani, A. R., and Lennartson, B., (2019), “Enhancing Digital Twins through Reinforcement Learning”, *IEEE 15th International Conference on Automation Science and Engineering (CASE)*, Vancouver, BC, Canada, 293-298.

Rezaei Aderiani, A., Hallmann, M., Wärmefjord, K., Schleich B., Söderberg, R., and Wartzack, S., (2021), “Integrated tolerance and fixture layout design for compliant sheet metal assemblies, *Journal of Applied Science*, 11(4): 1646.

Distribution of work

Paper A

Aderiani initiated the paper, performed the data collection and analysis and wrote the paper. Lindkvist developed an interface in RD&T to MATLAB. Wärmefjord and Söderberg contributed by providing feedbacks and reviewing the paper.

Paper B

Aderiani initiated the paper, performed the data collection and analysis and wrote the paper. Wärmefjord and Söderberg contributed by providing feedbacks and reviewing the paper.

Paper C

Aderiani initiated the paper, performed the data collection and analysis and wrote the paper. Lindkvist developed an interface in RD&T to MATLAB. Wärmefjord and Söderberg contributed by providing feedbacks and reviewing the paper.

Paper D

Aderiani initiated the paper, performed the data collection and analysis and wrote the paper. Wärmefjord and Söderberg contributed by providing feedbacks and reviewing the paper.

Paper E

Aderiani initiated the paper, performed the data collection and analysis and wrote the paper. Lindkvist developed an interface in RD&T to MATLAB. Lindau contributed by providing practical informations regarding fixture layouts and reviewing the paper. Wärmefjord and Söderberg contributed by providing feedbacks and reviewing the paper.

Paper F

Aderiani initiated the paper, performed the data collection and analysis and wrote the paper. Wärmefjord and Söderberg contributed by providing feedbacks and reviewing the paper.

زندگی صحنه ی یکتای هنرمندی ماست

هر کسی نغمه ی خود خواند و از صحنه رود

صحنه پیوسته به جاست

خرم آن نغمه که مردم بسپارند به یاد

"*Life is the sole scene that we can present our art.*
Everyone sings her song and leaves the scene.
The scene is continuously going forward.
Gratitude to the eternal songs."

Jaleh Esfahani, Translated by Abolfazl Aderiani

Contents

Acronyms

BIW	Body in white
CAT	Computer-aided tolerancing
DSI	Descriptive study I
DSII	Descriptive study II
DRM	Design research methodology
DOE	Design of experiments
FEM	Finite element method
GA	Genetic algorithm
KPC	Key product characteristic
MC	Monte carlo
MIC	Method of influence coefficients
MILP	Mixed-integer non-linear programing
MINLP	Mixed-integer non-linear programing
PSI	Prescriptive study I
PSO	Particle swarm optimization
RC	Research clarification
RMS	Root mean square
SSM	State-space modeling

CHAPTER 1

Introduction

The deviation of geometry from its nominal position is inevitable in the production of parts, because every production tool has limited precision and accuracy in production. Consequently, geometrical variation appears in the mass production of products. Such variation may create both functional and aesthetical problems in products. Moreover, they impose a combined quality cost, including scraps, repairs, and reworks. This combined quality cost is usually 10% to 40% of a company's revenue in the automotive industry [Thornton, 2004].

Production methods have shifted toward more automated processes in recent decades. This shift is predicted to continue at unprecedented speed in the coming decades [WMF, 2018]. Digitalization will be indispensable in the future of manufacturing and production. Consequently, the amount of data available to be used in production will increase considerably [Söderberg et al., 2017, WMF, 2018]. These trends are opening new opportunities to increase the quality of products while lowering their prices by individualizing production processes. Accordingly, the individualization of production processes to minimize geometrical variation can be pivotal in the competitive world of production and product development. This individualization is the framework on which the knowledge gaps and questions of this research are positioned and defined.

This framework is clarified in more detail in Section 1.1 and Section 1.2. The goals and focus of the research in this regard are subsequently introduced in Section 1.3. Section 1.4 identifies the research hypothesis and questions, and Section 1.5 clarifies the research scope. The final section of this chapter, Section 1.6, outlines the structure of this thesis.

1.1 Geometry assurance

Geometrical variation can be addressed in two general approaches. The first is to minimize sources of variation, and the second is to reduce the impact of the existing variation. In order to reduce the sources of variation, the introduced variation by manufacturing processes should be reduced. On the other hand, the effects of existing variation can be mitigated by modifying several factors, including concept design, production strategy, and tooling. These practices are commonly referred to as "robust design" [Thornton, 2004]. The set of activities practiced to address geometrical variation using both approaches is defined as geometry-assurance activities [Söderberg et al., 2006].

Geometry-assurance activities can be conducted in different phases of product development, including concept design, verification, and production phases (see Figure 1.1). In the concept phase, a key objective is to set design parameters so that the product is not sensitive to variations in parts. The fixture layout of assembly fixtures and split lines of parts are two examples of these design parameters [Madrid, 2018]. In the verification phase, the adjustment of locators and shimming can be predicted with variation simulation tools. Geometry-assurance activities in the production phase use inspection data to control production processes to minimize variation.

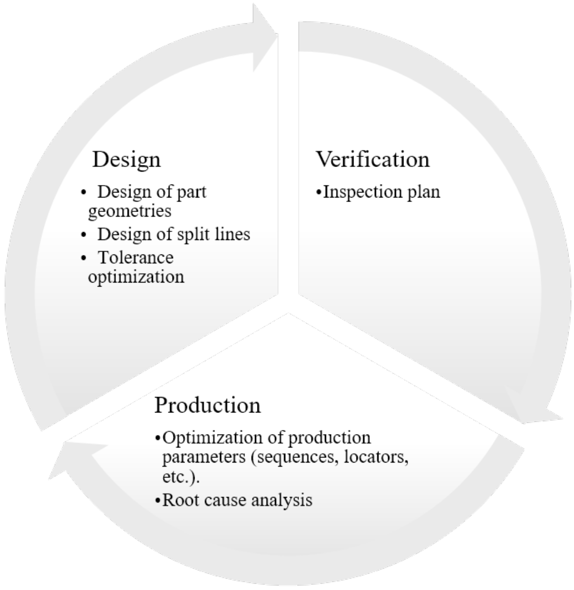


Figure 1.1: The geometry-assurance framework in three main phases of product realization adjusted from [Söderberg et al., 2006].

1.2 Individualization of assembly processes

The geometrical variation of assemblies, particularly sheet metal assemblies, is mainly a consequence of uncertainties in the geometry of parts. A main geometry-assurance activity in the production phase of these products is to adjust the production parameters so that the effects of these uncertainties are minimal. However, the improvement in geometrical quality that can be achieved by these adjustments is limited because the adjustments depend on the geometry of the parts, and the geometries are uncertain. The uncertainties result in each part having a unique geometry. Accordingly, the ideal settings for the production parameters differs for each individual assembly. As a result, to achieve the maximum geometrical quality, the assembly process should be individualized.

Taking advantage of advances in production automation and scanning the geometry of produced parts, several concepts have been presented to individualize production processes, particularly assembly processes [Schmitt et al., 2017, Söderberg et al., 2017, Polini and Corrado, 2020]. Among these concepts, Söderberg et al. have proposed the concept of a self-compensating assembly line in which the optimal production parameters are obtained for the assemblies by utilizing their digital twins [Söderberg et al., 2017]. This concept is named Smart Assembly 4.0. Figure 1.2 depicts a schematic image of this process.

In this individualized assembly line, the scanned data of produced parts will be utilized to generate a digital twin for each physical assembly. Since the objective is to maximize geometrical quality, the digital twin should predict the geometrical deviations of the physical assembly. Therefore, the digital twin should be a computer-aided tolerancing (CAT) model updated by scanned geometry of each part and used in variation simulations. The production parameters to be optimized include locators adjustments, weld sequences [Wärmefjord et al., 2016], and selection of the parts of each assembly.

After the optimal production parameters of the digital twin are calculated, they are applied to its corresponding physical assembly. Subsequently, the produced assembly is scanned, and feedback is sent to a learning agent to compare the obtained physical geometry against the results predicted by the digital twin. This learning agent utilizes reinforcement learning techniques to modify the predictions to minimize discrepancies between results of simulations and practice.

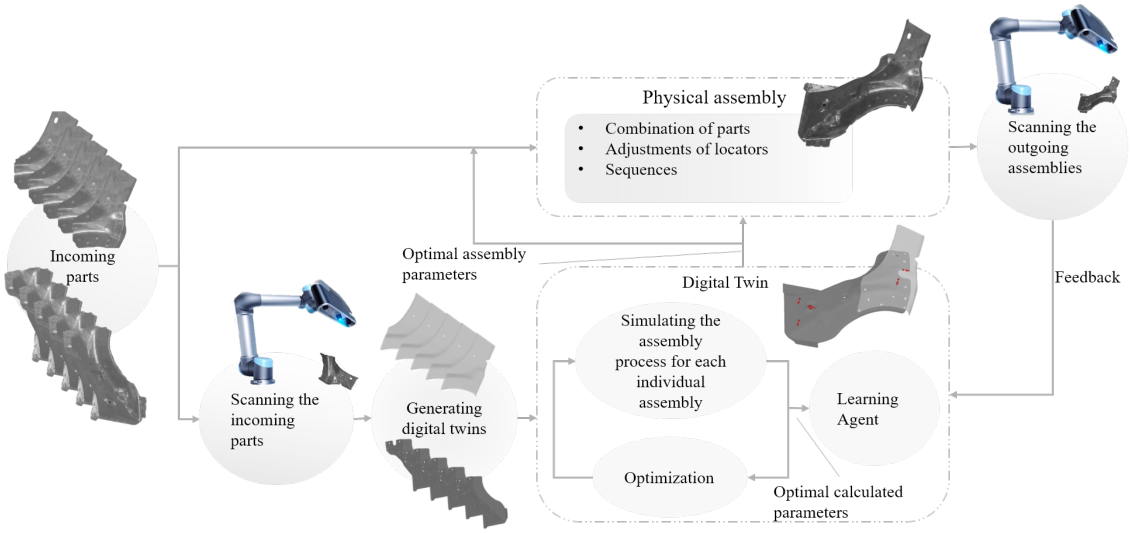


Figure 1.2: An schematic of the proposed concept of Smart Assembly 4.0 by Söderberg et al. [Söderberg et al., 2017]

1.3 Research focus and goals

This research focuses primarily on individualization in the assembly processes, particularly matching parts and locator adjustments, in the concept of Smart Assembly 4.0. It assesses the possibility of utilizing existing methods and tools in this concept, finding existing gaps and filling them by developing new methods and tools. The primary goal is to identify the potential and the means of individualization of the assembly processes to improve the geometrical quality of sheet metal assemblies through the aforementioned techniques. Accordingly, the primary hypothesis is that applying these techniques to an assembly line can improve the geometrical quality of the products. Hence, the research should also evaluate the validity of this hypothesis.

Matching parts is known as the selective assembly technique in the literature. The main focus in this context is to study existing applications and studies regarding this technique, finding the limits and challenges and developing tools and methods to cope with them. Thus, the primary goal is to discover the potential of this technique to improve the geometrical quality of assemblies. The existing selective assembly techniques are limited to linear and rigid assemblies. Consequently, this technique has not before been studied for sheet metal assemblies, which are usually compliant and non-linear.

Previous applications of locator adjustment in fixtures are limited to performing this technique on a batch of assemblies. Moreover, the scanned data of parts have not been utilized in predicting the adjustments. Therefore, the main goal of the research regarding locator adjustments is to discover the potential to individualize them based on the parts' scanned data.

Utilizing selective assembly and individualized locator adjustments separately might provide different results than when they are combined in a smart assembly line. Accordingly, the assessment of the possibility of accumulating these two techniques in one smart assembly line is the next objective of the research.

Another hypothesis is that the fixture layout utilized to assemble sheet metal assemblies plays a vital role in the achievable improvements. Therefore, the research results might be significantly dependent on this factor. Hence, this dependency shall be identified and considered in the results.

1.4 Research questions and hypotheses

The primary hypothesis of this research is that the geometrical quality of the sheet metal assemblies can be improved through individualization of the assembly processes, particularly by applying selective assembly and locator adjustments. The results of this research may help to evaluate this hypothesis. The first two research questions are formed based on this hypothesis.

Research Question 1: How can selective assembly techniques be utilized in spot-welded sheet metal assemblies?

This research question emerges from the preliminary review of the utilization of selective assembly techniques. It covers the problems and challenges involved in employing selective assembly techniques. The question probes the selective assembly methods and tools, the limits of their application, and the required developments.

Research Question 2: How can individualization in locator adjustments improve the geometrical quality of spot-welded sheet metal assemblies?

This research question addresses the second individual assembly process in focus in this research. This question also covers the possibility of gaining more significant improvement in individualizing locator adjustments, the potential challenges in calculating and performing them, and the methods of coping with those challenges.

Research Question 3: What are the effects of combining selective assembly and individualized locator adjustments in a smart assembly line?

The third research question concerns the possibility of accumulating improvements from both individualization methods. It concerns how different combinations of these techniques can be employed in a smart assembly line and what will be their outcomes.

Research Question 4: What are the effects of assembly fixture layout on the achievable geometrical improvements of selective assembly and individualized locator adjustments?

This research question addresses the main concern about the dependency of the previous questions' answers on fixture layouts. It also covers the strategy that should be followed in designing a fixture layout to achieve the preferred output of the individualization techniques.

1.5 Delimitations

Individualization in the assembly processes is not limited to selective assembly and locator adjustments. Other parameters in the assembly process can be individualized, including the sequence of welds. Nevertheless, this research focuses on adjusting the locators and on selective assembly techniques, since the other parameters are being studied in parallel in the same research group.

The research questions can be answered with respect to, for example, logistical, economic, and sustainability priorities. Nevertheless, this thesis focuses on the technical aspects of this question, particularly geometrical assurance. Therefore, the main gaps from these aspects are addressed in the appended papers. However, presenting the potential of individualization in this research can motivate other researchers to study other elements of it.

The sample cases utilized in this research for testing the developed methods are spot welded assemblies. There are other types of joints and assemblies in different industries, including seam welds, fasteners, and glues, although spot welds dominate the automotive and aerospace industries. Moreover, parts' mechanical properties in this research are limited to linear materials, particularly metals. Nevertheless, the methods and tools presented can be applied to all types of assemblies. Although the level of improvement may differ, it is expected that the presented method can improve the geometrical quality of other types of assemblies.

1.6 Outline

This thesis is divided into six chapters. The first chapter introduces the research background, the problems that the research is trying to solve, its goals, and the questions addressed. Chapter 2 presents the frame of reference. This chapter reviews the main topics with which this research deals. Chapter 3 discusses the methodology employed in conducting this research. The results of the appended papers and their connection to each other are presented in Chapter 4. Subsequently, the Chapter 5 discusses how these results answer the research questions, and the main conclusions of the research are summarized in the Chapter 6.

CHAPTER 2

Frame of Reference

This research draws upon concepts from several fields . An overview of each field is given in this chapter. Figure 2.1 overviews the topics related to this research.

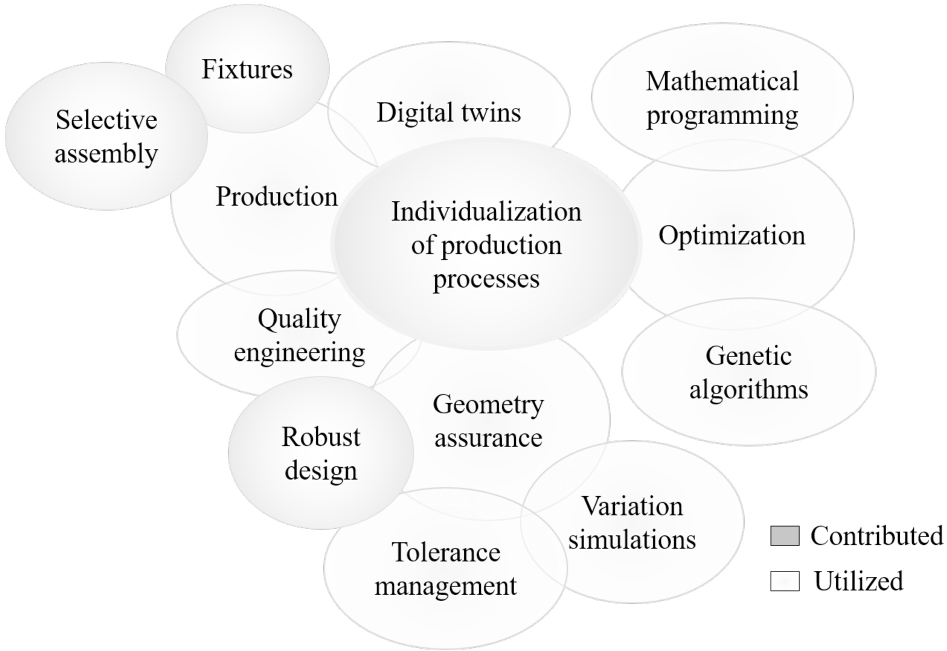


Figure 2.1: The related and contributed fields of studies.

The primary focus of the research is to study individualized assembly processes to improve the geometrical quality of the assemblies. Hence, different criteria for the assessment of geometrical quality are defined in Section 2.1. Section 2.2 provides a brief background of geometry assurance, particularly tolerance analysis and variation simulations. Afterward, fixtures and the concept of part fixation are reviewed in Section 2.3. This research focuses on the selective assembly technique. Accordingly, Section 2.4 of this chapter reviews this technique. Section 2.5 introduces digital twins. Section 2.6 overviews optimization, since this research utilizes different optimization techniques in presenting new methods and tools.

2.1 Quality engineering

This research aims to improve the geometrical quality of sheet metal assemblies. Therefore, this section summarizes definitions of quality, particularly geometrical quality, along with the criteria used to measure it.

2.1.1 Quality definition

Quality does not have a well-accepted general definition. Nevertheless, certain definitions are common, particularly in the context of engineering. The American Society for Quality (ASQ) defines quality as "the characteristics of a product or service that bear on its ability to satisfy stated or implied needs"[1]. The definition of quality, by the ISO 8402 standard, is "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs." Based on these definitions and a general understanding of quality, it can be defined as the degree to which product performance meets stakeholders' expectations.

Quality loss is an alternative term introduced by Taguchi et al. [Taguchi et al., 1989] . They define quality loss as the costs imposed upon the society by the product during the product's lifespan. This definition has been expanded to the product and production-development stages. Accordingly, this loss occurs not only when the criteria of quality measurement fail to pass their limits. Every deviation from the nominal characteristics of the product is associated with a loss. A variety of loss functions are introduced in the literature to define the relationship between losses and deviations [Phadke, 1995].

2.1.2 Geometrical quality

The ideal geometry of a product is the geometry intended by the designer, usually referred to as the nominal geometry. However, due to production limits, the accuracy and precision with which this geometry can be achieved are limited. Consequently, manufactured products deviate from their nominal geometry. These deviations can cause functional and aesthetical problems in the final product, so minimizing them is desirable. It is supposed that the minimal quality loss occurs when the geometry is nominal. Accordingly, different criteria for assessing geometrical quality are functions of the geometrical deviations.

The criterion of geometrical quality for a single part of an assembly can be defined as a geometrical deviation in a single point, several areas, or across the entire product. When the goal is to assess the deviation of the entire geometry of the product, some representative points of the overall geometry are selected, and the root mean square (RMS) of deviations from these points can be considered [Söderberg, 1994a] as the criteria of the geometrical quality evaluation. Equation 2.1 illustrates this definition.

$$RMS_d = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_i)^2} \tag{2.1}$$

In this equation, d_i represents the deviation of the ith point, and n is the number of all representative points of the geometry. RMS_d is a proper criterion for geometrical quality assessment when the goal is to improve geometrical quality by changing certain design or production parameters. Changing some parameters may improve the geometrical quality of one area and worsen it in others. Hence, if only specific points are considered in the evaluation of quality, the changes may reduce quality in other points.

In the mass production of parts and assemblies, the deviation of each point may vary for each product. Therefore, other criteria are employed to evaluate the geometrical quality of the entire batch of assemblies. These criteria are defined based on the statistical evaluation of the deviations. For each point, a lower limit (LL) and an upper limit (UL) define the boundaries of allowable deviations from the nominal value.

The deviations from nominal geometries commonly follow a normal distribution. Even if the distribution of deviation for a single character is non-normal, the distribution of the stack up deviations will be normal. This is because, based on the central limit theorem, if variables contributing to deviations are independent and random, the distribution of the collective deviations tends to be normal.

A normal distribution can be specified by mean value and standard deviation. Accordingly, these two parameters can be utilized to evaluate the geometrical quality of a batch of parts or assemblies.

[1] https://asq.org/quality-resources/quality-glossary

For each geometrical specification, the mean value is referred to as the mean deviation. Equation 2.2 presents this parameter for point i. In this equation N represents batch size.

$$\bar{d}_i = \frac{1}{N}\sum_{j=1}^{N} d_{ij} \tag{2.2}$$

Variation is statistically estimated as σ^2 where σ indicates the standard deviation of the variable. Equation 2.3 presents definition of σ.

$$\sigma_i = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}(d_{ij}-\bar{d}_i)^2} \tag{2.3}$$

The variation represents the precision, and the mean deviation presents the accuracy of dimensions. The capability index C_p is introduced [Taguchi et al., 1989], as defined in Equation 2.4, to evaluate the variation of a geometrical specification relative to the requirements.

$$C_p = \frac{UL-LL}{6\sigma} \tag{2.4}$$

C_p evaluates the variation of a geometrical specification relative to the maximum allowable variation. A $C_p \geq 1.67$ indicates the fulfillment of the required variation by 99.99% of the products. However, this index does not consider the mean deviation of the geometrical specification. To include the mean deviation in addition to the variations, C_{pk} is defined as presented by Equation 2.5.

$$C_{pk} = \min\{\frac{UL-\bar{d}}{3\sigma}, \frac{\bar{d}-LL}{3\sigma}\} \tag{2.5}$$

C_{pk} is equal to C_p if the mean deviation is zero, and it is less than C_p if the distribution has a mean deviation. The difference between these two criteria of variation (accuracy) and the mean deviation (precision) and their relation to the capability indexes are illustrated in Figure 2.2.

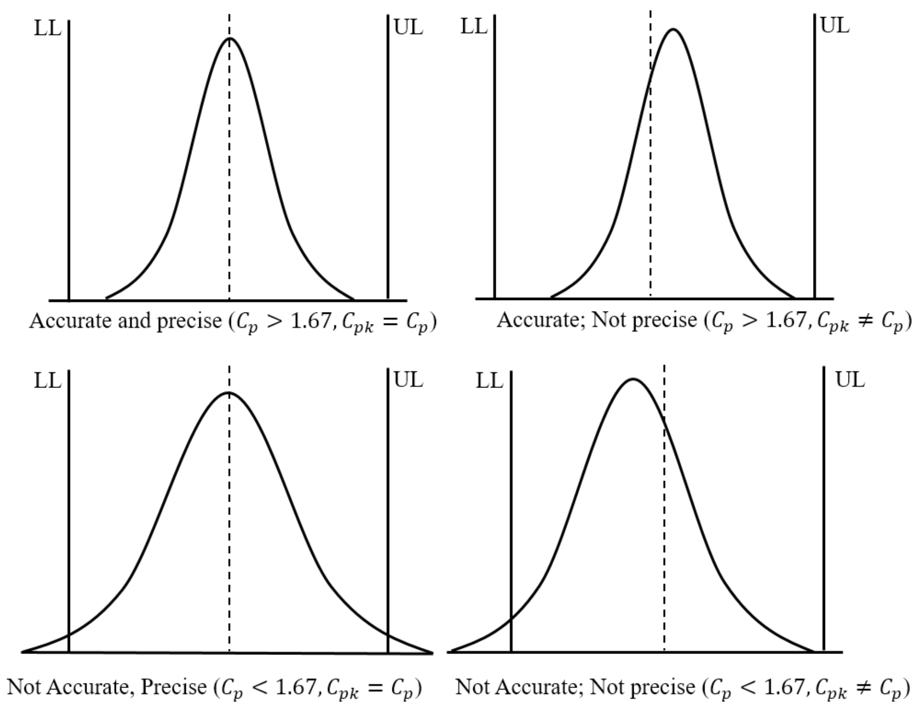


Figure 2.2: Difference between variation (accuracy) and the mean deviation (precision).

The charts presented in this figure visualize the distribution for a dimension where a dashed line indicates the nominal mean value. Hence, the accuracy is higher for distributions whose mean value is closer to the nominal. Nevertheless, the produced parts can have a high accuracy without being precise. Although the mean value of the dimension is close to the nominal, some individual dimensions have higher deviations than the specified limits. As a result, to improve the geometrical quality of a batch of parts or assemblies, both variations and the mean deviations of the specified dimensions should be considered.

To consider the geometrical quality of all areas of the product in a batch, both variation and the mean deviation of the corresponding points should be considered. Variation is commonly measured by six times the standard deviation, known as six sigma. The average variations are measured by utilizing the RMS of six sigma in all corresponding points. This parameter is represented by RMS_v. The RMS of mean deviation is also considered to evaluate accuracy, presented by RMS_m. Equations 2.6 and 2.7 present definitions of these parameters.

$$RMS_v = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(6\sigma_i)^2} \tag{2.6}$$

$$RMS_m = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\bar{d_i})^2} \tag{2.7}$$

In these equations, n represents the number of points considered for evaluation.

2.2 Geometry assurance

Various activities aim to cope with the problem of geometrical variation and are referred to as geometry-assurance activities. As shown in Figure 1.1, geometry assurance can be performed from the concept design phase to mass production. Nevertheless, to cope with variation, it is essential to know the causes and sources thereof.

The geometrical variation of a final product depends primarily on the geometrical variation of its parts. The variation in parts comes from the accuracy and precision of production tools and variation in manufacturing processes. The variation of assembly processes contributes to this complexity, resulting in final variation of the product. The variation of assembly processes can result from assembly fixtures, welding tools, and other involved determinants. Söderberg et al. [Söderberg et al., 2006] have visualized the contribution of different sources of variation in Figure 2.3.

2.2.1 Tolerance management

A method for controlling variation on both the part and assembly level is to allocate tolerances to dimensions and forms. Tolerancing has been the subject of a large variety of studies [Shah et al., 2007, Hong and Chang, 2002]. Allocating tolerances to dimensions and forms can be performed using two different approaches. The first is top-down tolerancing. In this approach, the tolerances of the final product are initially defined. Afterward, they are broken down into subassemblies and parts [Söderberg, 1993, Söderberg, 1994b, Lööf, 2010]. The second approach is referred to as the bottom-up approach. In this approach, the tolerances of dimensions and forms on the part level will be defined based on previous experience or production limitations. Hence, the final tolerances will be evaluated for the specified function of the product. If tolerance limits of the final product do not meet requirements, the primary tolerances should change and repeat themselves until the desired tolerances on the final product can be achieved. A combination of both approaches is often used in practice.

In both tolerancing approaches, it is essential to predict the accumulation of tolerances from different sources. This prediction can be conducted through a tolerance analysis. A variety of methods and tools for tolerance analysis have been presented in previous studies and are reviewed in [Shah

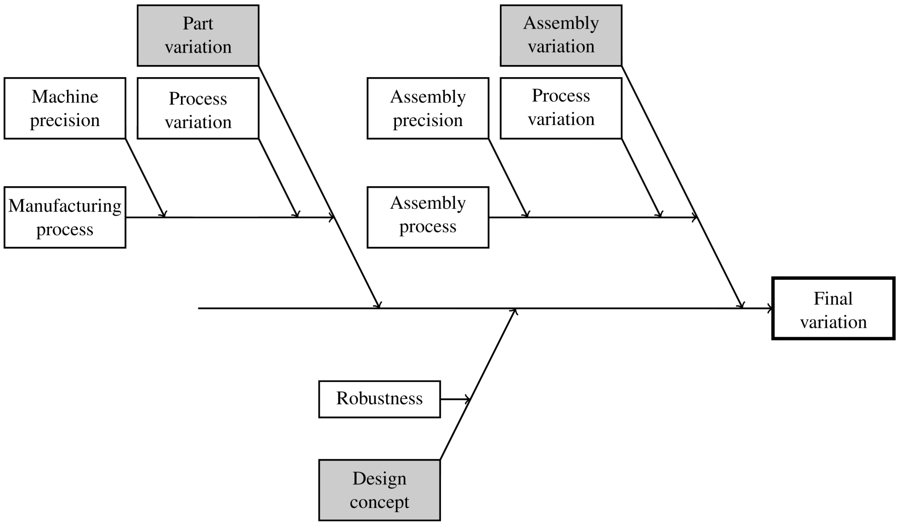


Figure 2.3: Contributors to final geometric variation [Söderberg et al., 2006].

et al., 2007, Chase and Parkinson, 1991, Gao et al., 1998, Hong and Chang, 2002, Nigam and Turner, 1995, Hong and Chang, 2002].

The relation between the input and output tolerances (i.e., variations) can be expressed by a general distribution function of dimensions as indicated by Equation 2.8.

$$Y = f(X_1, X_2, \dots, X_n) \tag{2.8}$$

The input parameters of X_i represent the input variations, and Y is the response of assembly to them. A probability distribution can be defined by its moments. Hence, the tolerance analysis challenge is to obtain the moments of Y when the moments of the input variables are known. Definitions of the first to the fourth moments are presented by Equations 2.9, 2.10, 2.11, and 2.12, respectively. The first, the second, the third, and the fourth moments are referred to as the mean value (μ_i), standard deviation (σ_i), skewness coefficient (γ_i), and kurtosis coefficient (Γ_i), respectively. The last two moments are zero for a normal distribution. Accordingly, if the variation is considered as normal only μ_i and σ_i are required to be determined.

$$\mu_i = \int x_i w_i(x_i) dx_i \tag{2.9}$$

$$\sigma_i^2 = \int (x_i - \mu_i)^2 w_i(x_i) dx_i \tag{2.10}$$

$$\gamma_i \sigma_i^3 = \int (x_i - \mu_i)^3 w_i(x_i) dx_i \tag{2.11}$$

$$\Gamma_i \sigma_i^4 = \int (x_i - \mu_i)^4 w_i(x_i) dx_i \tag{2.12}$$

In these equations, w_i is the probability density function of the input variables. Using the moment equations is not practical for assemblies in which the analytical function of the input and output variations is not exact. Accordingly, different methods try to present practical methods for obtaining these moments.

Several methods determine the moments from some of the Tailor expansion coefficient of Y. The formulation of this expansion for the first order is presented in Equation 2.13. In this equation, X_i represents the input variations, and μ indicates the mean value thereof.

$$f(X_1, X_2, \ldots, X_n) \approx f(\mu_1, \mu_2, \ldots, \mu_n) + \sum_{i=1}^{n} \frac{\partial f(\mu_1, \mu_2, \ldots, \mu_n)}{\partial x_i} (X_i - \mu_i), \tag{2.13}$$

Depending on the amount considered for X_i, the tolerance analysis can be *worst case* or *statistical*. If all X_is are considered at their worst value simultaneously, the method is the worst case. Nevertheless, the probability of having all input variations at their worst value is commonly low. Therefore, this method is pessimistic and may increase production costs [Nigam and Turner, 1995]. However, in a statistical method, the statistical distribution of input tolerances is considered for calculating output variations. Hence, this method is more realistic.

If the relation between the output and input variations can be expressed as a linear function, the variation of output will have a normal distribution based on the central limit theorem. Therefore, only the first two moments are required to be determined.

On the root sum square (RSS) method, the RSS of sensitivity coefficients of the Taylor expansion are considered to obtain the second moment of the variation distribution. Equation 2.14 presents the formulation of this relation [Evans, 1975b]. In this equation, T represents the output variation and t_is indicate the input variations.

$$T = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f(\mu_1, \mu_2, \ldots, \mu_n)}{\partial x_i} t_i \right)^2} \tag{2.14}$$

In contrast to the worst-case method, the RSS method is considered an optimistic prediction of the output variations [Nigam and Turner, 1995]. Consequently, a modified version of this method or a combination of both methods is considered a more practical method in analytical tolerance analysis [Chase and Parkinson, 1991, Wu and Tang, 1998, Lööf, 2010].

For non-linear response functions of Y higher orders of Tailor expansion can be utilized to determine the moments [Evans, 1975b, Evans, 1975a].

If an explicit function of Y is not available, the Taguchi method and its modified versions can determine the output variations. These methods determine the output variation by utilizing the results of some designed experiments in full or fractional factorials [Nair et al., 1992]. Statistical independence and normal distribution of the inputs are two main assumptions in this method.

Monte Carlo (MC) simulations are another approach in tolerance analysis. On this method, a large number of samples of the product will be generated. For each sample, the input values are generated based on their distribution, and the output is calculated. Therefore, the distribution of the outputs can be predicted by analyzing the samples generated. Both linear and non-linear relations can be simulated by this method.

The advantage of analytical methods of tolerance analysis is their low cost of computation. However, the implementation of these methods can be complicated, and their accuracy has also been questioned [Cai et al., 2006]. On the other hand, MC simulation has a high calculation cost, whereas its implementation is more straightforward and can be used for various functions.

2.2.2 Variation simulations

The relation between the input and output variations can be so complicated that utilizing analytical methods to predict output variations may be impractical, if not impossible. Variation simulations are developed to address this problem. Variations of both rigid and non-rigid products can be simulated by utilizing variation simulation methods and tools. In addition, these tools can determine an index to measure sensitivity to a locating scheme. Moreover, the contribution of different inputs to variation of specific output and presenting the variation propagations by color coding are other advantages that can be utilized by these tools [Söderberg and Lindkvist, 1999].

Different sources of variation may be added to these simulations, including part variations and fixture variations. The input variation of a simulation can be the scanned geometry of the produced parts (in the production phase), or they can be generated using the MC method. Variation simulations can also be used to predict the variations of assemblies by simulating the assembly procedure.

Compliant assemblies, part deformations, gravity, and spring back can affect assembly variations. The finite element method has been utilized to include these factors' effects in the simulations.

Liu et al. [Liu and Hu, 1997] presented a simplified assembly process in four stages to simulate the assembly process. In the first stage, the parts are positioned into assembly fixtures. Subsequently, the welds are applied. The assembly is then released from the fixture, and stresses induced during the assembly procedure will cause spring back. Figure 2.4 illustrates this process.

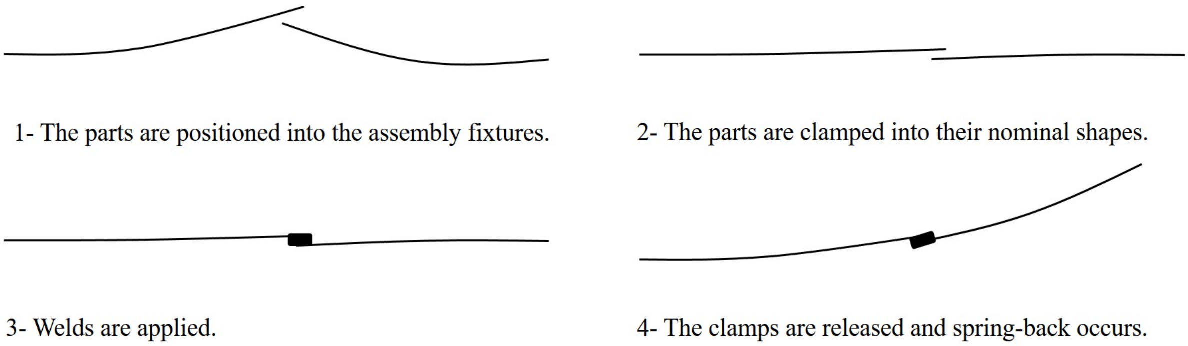


Figure 2.4: Four main steps in simulation of an assembly process.

This process can be simulated by employing two finite element simulations. The clamping forces ($[F_c]$) are determined in the first simulation from the part deviations ($[D_1]$). Equation 2.15 represents the relation utilized between these parameters.

$$[F_c] = [K_1][D_1] \tag{2.15}$$

In the simplified procedure of assembly depicted in Figure 2.4, the deformations applied by welding guns are neglected. Hence, the clamping forces before and after welding can be considered equal. The stiffness matrix of the assembly ($[K_2]$) can be determined by joining the nodes of parts in the welding points. Accordingly, the assembly deviations can be determined from Equation 2.16 using the second FE simulation.

$$[D_2] = [K_2]^{-1}[F_c] \tag{2.16}$$

This procedure can be conducted in each MC iteration to determine the variation and distribution of the assembly. However, the calculation cost of such a procedure can become significant. To address this problem, Liu and Hu [Liu and Hu, 1997] have proposed substituting a linear relationship between the assembly deviations and part deviations. Equation 2.17 presents this relation, in which $[S]$ is defined as the sensitivity matrix. The sensitivity matrix can be determined using two FE simulations. This method of variation simulation is referred to as method of influence coefficient (MIC).

$$[D_2] = [S][D_1] \tag{2.17}$$

A significant drawback of MIC that it neglects contact between parts. During a physical assembly process, the parts can interact in the contact areas. These interactions might affect the geometry of the assemblies. Further, the contact areas and their forces might change with alternate part deviations. Therefore, the relation between deviations of the assemblies and the part deviations depends on the deviations of each part, and it is not a linear relation. Consequently, considering a linear relation between them can result in serious simulation errors.

Dahlström et al. [Dahlström and Lindkvist, 2007] have addressed this issue by developing a modified MIC method in which the stiffness matrix is updated in each iteration of MC simulations. Wärmefjord et al. [Wärmefjord et al., 2008] further improved this method by automating the contact detections. Lindau et al. [Lindau et al., 2016] have developed a further method of contact modeling, based on solving a quadratic optimization problem. An efficient method of contact modeling in rivet assemblies is developed by Lupuleac et al. [Lupuleac et al., 2011].

The input part variations for rigid parts and assemblies are commonly generated by deviating the locators from their nominal location, in each MC iteration. If a part is rigid, the part variation in the locating points can be substituted with an identical locator variation in the same area. However, this substitution cannot be made for compliant parts. The fixture and locators in compliant parts are considered rigid. Hence, substituting the part variations with locator variations in the same areas can result in a completely different output variations. Consequently, in compliant variation simulations, it is vital to consider the part variations as they are in practice.

One way to address this issue is to scan the produced parts and utilize them. This method is possible only for the produced parts and cannot be utilized during the product development phase or to predict variations in parts that are not yet produced. Nevertheless, this limitation does not exist for digital twin based simulations, as utilized in this research.

A primary application of variation simulations is to predict variation in products whose parts are not yet produced. Therefore, the non-ideal geometry of the parts should be predicted based on the measurement data of the previously produced parts or on simulation results for the production process of each part. This issue is an ongoing topic in variation simulation research.

Lindau et al. [Lindau et al., 2013] have utilized PCA methods to identify the main deformation modes of the parts and utilize those modes to represent the produced parts. Franciosa et al. [Franciosa et al., 2011] have developed a method based on mesh morphing to generate the deformed shapes of parts from the measurement data in several points of each part. Babu et al. [Babu et al., 2018] have also developed a probabilistic model for generating the deformed shapes of the input parts based on available measurement data.

Schleich et al. [Schleich et al., 2014, Anwer et al., 2014] have developed the skin models shapes method to generate input part variations and transfer them to finite element simulations. They have divided the variations into systematic and random variations. This method also utilizes some measurement data from the non-ideal parts to train the skin models.

Nowadays, the variation simulations with more complexities, including weld sequencing [Wärmefjord et al., 2010], gravity, and heat effects [Lorin et al., 2012], can be conducted by available commercial tools for variation simulations. The RD&T program[2] is one of the tools that can perform both rigid and compliant simulations. This program can also conduct the simulations by considering contact modeling, weld sequencing, and other essential factors. Therefore, this program is utilized in this research to predict the geometrical quality of assemblies in individualization. Some assumptions have been made in this tool for variation simulation, including that deformations do not exceed the linear elastic range, fixtures and welding tools are not flexible, that deformations due to temperature are negligible, materials are isotropic, and the stiffness matrix remains constant for the deformed part shapes. The detailed procedure of the variation simulation method utilized in RD&T is illustrated by [Söderberg and Lindkvist, 1999] and [Lindkvist and Söderberg, 2003].

2.3 Fixtures

Fixating parts and products are among the preeminent factors in defining the geometrical quality of products. The fixation is performed through the utilized fixtures or the connecting points where different parts of a product are assembled. This section addresses this context, introducing the concept of fixtures and locating schemes. Subsequently, locator adjustments as a geometry-assurance technique are illustrated.

[2]www.rdnt.se

2.3.1 Locating schemes

To hold a part in a specific position, at least six degrees of freedom of the part should be locked. These degrees of freedom are translations and rotations around x,y and z axes in an arbitrary coordinate system. Accordingly, a fixture layout should fixate at least these degrees of freedom by utilizing different types of locators. Different arrangements of locators can be utilized to achieve this goal. Together, the locators of a part constitute a locating scheme. A common locating scheme for positioning rigid parts is a so-called 3-2-1 locating scheme, as illustrated in Figure 2.5 [Söderberg et al., 2006].

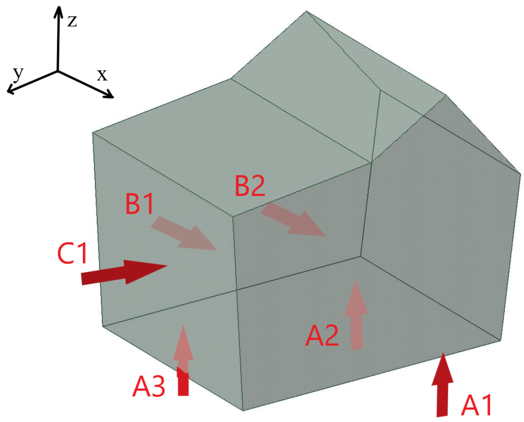


Figure 2.5: A 3-2-1 locating scheme.

The number of locators for compliant parts can be more than six. These additional locators are referred to as supports. For instance, in a sheet metal part, the locating scheme can be $N-2-1, N>3$ [Cai et al., 1996]. This formulation means that the number of applied locators perpendicular to the sheet surface is more than three. The reason for having additional locators is usually to withstand external forces, including gravity.

2.3.2 Fixture layouts

Fixtures can be utilized in different production processes, including machining, drilling, and assembly. Nevertheless, the function of fixtures differs depending on their application. The primary function of fixtures in part production processes, including machining and drilling, is to avoid machining forces from changing the position of the part or causing plastic deformations [Menassa and DeVries, 1989].

The function of fixtures in the assembly processes, particularly assembly of sheet metals, is different. Fixtures can be utilized in two stages of an assembly process. The first stage is to fixate the parts during the assembly process, and the second stage is to fixate the assembly for measurement. The utilized fixtures during the first step are referred to as the *assembly fixtures*, and the fixtures of the second step are *measurement fixtures*.The main objective of an assembly fixture is to maximize robustness, minimizing the effects of part variation and process variation to the assembly variation.

A fixture layout is a combination of locating schemes used for each part in the fixture. Several types of locator are used in fixtures, but 4 -way pins, 2-way pins, and clamping units are the typical locators. The 4-way pins are sometimes referred to as a hole and the 2-ways pins as a slot. The holes and slots can be clamped or not. The degrees of the freedoms that each type of locator locks differs. A hole locks the transformations of the parts in the normal plane, where it is located. A slot locks the translation of the part in the perpendicular direction to the slot direction and the normal plane. If the hole or slot is clamped, they lock the translation and rotation in the normal direction, in addition to the other locking directions. Figure 2.6 depicts an example of a sheet metal part located using different types of locators.

In parts with complex geometries, particularly for rigid parts, it can be complicated to determine whether a fixture layout locks all degrees of freedom of all parts.

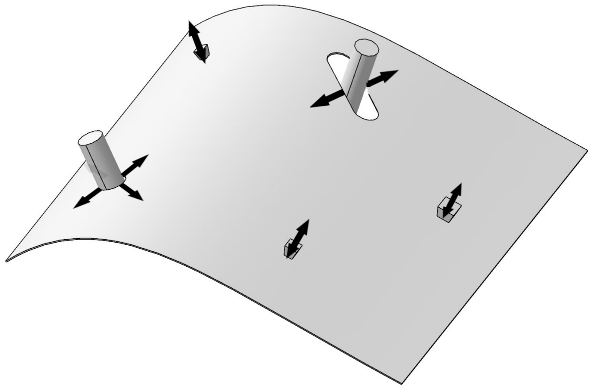


Figure 2.6: Different types of locators and their locking directions in an assembly fixture.

A fixture layout that locks all these degrees of freedom (i.e., avoids rigid body motion of each part) is defined as a deterministic fixture layout. A fixture layout for a part is deterministic if its Jacobian matrix (J) has a rank of equal or more than six [Asada and By, 1985]. Equation 2.18 presents the formulation of J for a fixture layout in which the coordinates of the locating points are presented by $[x_q,\ y_q,\ z_q]$ to locate the point of q. The normal vector of each locking direction in locator q is also presented by $[a_q,\ b_q,\ c_q]$. Thereby, the number of rows in this matrix representing each locator is equal to the number of directions that each locator locks.

$$J = \begin{bmatrix} a_1 & b_1 & c_1 & c_1y_1 - b_1z_1 & a_1z_1 - c_1x_1 & b_1x_1 - a_1y_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_q & b_q & c_q & c_qy_q - b_qz_q & a_qz_q - c_qx_q & b_qx_q - a_qy_q \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_f & b_f & c_f & c_fy_f - b_fz_f & a_fz_f - c_fx_f & b_fx_f - a_fy_f \end{bmatrix} \tag{2.18}$$

The Jacobian matrix is utilized in rigid variation simulations to determine variations of different points. Equation 2.19 presents the relation between the deformation of an arbitrary point c when the locating points are deviated as δ.

$$\delta_a = A\delta_{locating\ point} \tag{2.19}$$

where each row in A is defined by

$$a_i^T = \begin{bmatrix} (\mathbf{x}_i \times \mathbf{m}_i)^T & m_i^T \end{bmatrix} J^{-1}, \tag{2.20}$$

In this formulation, $\mathbf{x}_i$ represents coordinates of c, and $\mathbf{m}_i$ is the direction in which deviation of point c is intended to be determined. Equation 2.19 is the base of most variation simulations tools for rigid bodies [Söderberg and Lindkvist, 1999]. Cai et al. [Cai, 2008] have developed a two-step linear method of determining variations in rigid assemblies utilizing this equation.

2.3.3 Locator adjustments

More than a thousand points in a typical body in white (BIW) are required to be produced within a tolerance range of 2 mm. Given that BIW consists of roughly 200–500 panels and sub-assemblies, and the stack-up deviations of each assembly, achieving the final geometrical tolerances is challenging. Each typical assembly fixture commonly has 2 to 25 clamping units, in which there are roughly more than 20 parts and fasteners. This variety adds to the complexity of setting up a fixture to achieve the required accuracy.

Shims are thin metal plates in various thicknesses commonly used to adjust the locating points of each locator. They can also be used to compensate for gaps generated between parts subject to wear. Figure 2.7 depicts a type of shim commonly used in assembly fixtures of BIW. The proper shim thicknesses are traditionally determined based on previous experience or trial and error.

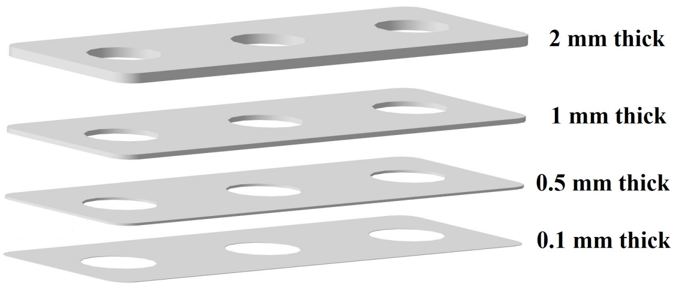


Figure 2.7: A common type of shim in assembly fixtures of BIW.

Adjustable locators in assembly fixtures are another solution by which for fulfill the same objective as shims. Locator adjustments can improve the geometrical quality of products by performing minor adjustments to locators in their steering direction.

The methods of determining the required adjustments for obtaining the maximum geometrical quality have been the subject of several studies. A virtual trimming toolbox has been developed by Lindkvist et al. [Lindkvist et al., 2005] in a CAT tool. The input of this toolbox for determining the adjustments is the inspection data of parts in the pre-production phase. This toolbox is limited to rigid assemblies. Consequently, the adjustments can be determined for only six locators. There have been some attempts to train metamodels to calculate adjustments [Germer et al., 2014, Beckmann et al., 2015]. In these methods, the input data of the training phase are the amount of each adjustment and corresponding deviations in the assemblies produced. Using the locating force to predict these adjustments is another method that has been developed by Keller [Keller, 2014, Keller and Putz, 2016]. The application and studies of locator adjustments have been limited to a batch of assemblies. Thus, the scanned data of the parts have not been utilized to determine these adjustments. Forslund et al. [Forslund et al., 2018] have utilized locator adjustments for rigid bodies to improve the geometrical quality and strength of the rear structure of a jet engine. In this study, the locator adjustments technique is conducted individually for each blade of the structure, considering the blades are rigid.

2.4 Selective assembly

Matching parts in mass production of assemblies is known as the selective assembly technique in the literature. This technique can improve assemblies' geometrical quality by selecting individual parts based on their dimensions instead of assembling them randomly. The assembly process using this technique is explained using an example. Consider an assembly of three components, A, B, and C, as shown in Figure 2.8 (the word "components" refers to the elements of the assembly, and the word "parts" refers to individual produced parts of that element in mass production). If the batch size, the quantity of all assemblies to be produced, is 1000, then 1000 parts from each component should be produced. The nominal dimensions of A, B, and C are L_1, L_2, and L_3, respectively. Nevertheless, the dimensions produced may diverge from the nominal dimensions. Therefore, the dimensions produced should be measured for each part. These parts are then divided into several groups, six groups as an example, based on their dimensions. The final step is to match these groups so that assembling their parts will result in minimal variation in the target dimension of assemblies. This requires finding the optimal combination of A_i, B_j and C_k where $i, j, k \in \{1, 2, 3, \ldots, 6\}$ so that the variation of the target dimension in the assembly becomes minimal. For example, the solution of this optimization problem can be $(A_1B_1C_4)$, $(A_2B_5C_1)$, $(A_4B_2C_3)$, $(A_5B_4C_6)$, $(A_6B_6C_5)$ and $(A_3B_4C_2)$, where $(A_1B_1C_4)$ means that group number one from component A, group number one from component B, and group number four from component C should be assembled together.

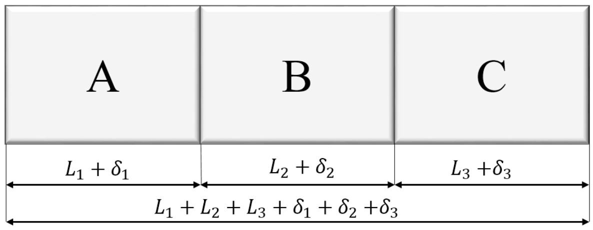


Figure 2.8: A sample linear assembly of three components.

Selective assembly techniques have been utilized since the 1940s in the engine and bearing industries [Mansor, 1961]. However, the mismatching problem troubles this technique. After dividing the parts into several groups and matching them, the number of parts in the matched groups may not be equal. Consequently, some parts from larger groups will become superfluous. Most early studies about selective assembly are concerned with this problem and present different methods to solve it [Mansor, 1961, Fang and Zhang, 1995, Chan and Linn, 1999, Pugh, 1992]. Generating groups so that the probability of getting the same number of parts is maximal is an example of such attempts [Chan and Linn, 1999]. These methods are based mainly on statistical methods and the assumption that the parts' variation follows a normal distribution.

To divide the parts into several groups based on their produced characteristics is also referred to as *fixed bin selective assembly* [Tan and Wu, 2012] or *selective assembly with classes* [Lanza et al., 2015]. In contrast, another method is to find a match for each individual part and assemble them. This method is referred to as *individual selective assembly* [Lanza et al., 2015] or *direct selective assembly* [Tan and Wu, 2012]. Tan and Wu [Tan and Wu, 2012] have discussed the deterministic methods that can be utilized to solve these two categories of selective assembly problems: primarily, mixed-integer linear programing (MLP) or mixed-integer non-linear programming (MINLP) that can be utilized to solve combinatorial problems. The main issue with these methods is that size of the problem increases exponentially with an increase in the number of parts or components. Consequently, it is not practical to use them for real size selective assembly problems.

Several studies have focused on finding the optimal combination of the groups of parts for a specific batch of parts. They have mainly utilized meta-heuristic optimization algorithms, particularly genetic algorithms (GA) and particle swarm optimizations (PSO) [Kannan et al., 2005, Kumar et al., 2009, Kannan et al., 2009, Asha et al., 2008, Kumar et al., 2007, Ponnambalam et al., 2006, Rezaei Aderiani et al., 2018]. These studies are concerned mostly with having minimal or zero surplus parts and minimizing the variation of the target dimension in the assemblies. Based on this concept, an optimization is performed for each batch of parts independently. This concept contrasts with the fixed bin method, where incoming parts are allocated to bins based on their produced dimensions, and the production can be conducted continuously. However, the implemented concept in the engine and bearing industries is the fixed bin concept, which makes the mass production practices being performed at the required speeds. It is not clear, however, how practical it is to match the groups of parts for each batch independently.

Lanza et al. [Lanza et al., 2015]ave evaluated employing selective assembly along with adaptive manufacturing in cyber-physical production systems. The objective is to minimize production costs. The optimization is conducted for the entire production system, and parameters including the inventory size are also considered. Combining these two techniques can result in individualized production system in which the process parameters of one part are adjusted based on the measurement data from the other part produced. This system is simulated for a sample case, and the results indicate 38% savings in production costs, compared to the conventional production system.

Ju et al. [Ju et al., 2017] have considered the effects of limiting the buffer capacity in production through selective assembly. Velasquez and Nof [Velásquez and Nof, 2009] have evaluated the required design and production process adaption for utilizing selective assembly.

Despite being the subject of a significant number of studies in the literature, the application of this technique has been limited to rigid and linear assemblies, particularly the piston-engine, bearing assemblies, and similar products. One reason may be the added costs of employing this technique in an assembly line, along with the technical difficulties and limitations in scanning and automating the assembly procedure. However, the technology seems to be near completion and will be more accessible soon that the associated costs with employing this technique will reduce to acceptable levels. Thereby, this research initiates the development of selective assembly application to the assembly of spot-welded sheet metals.

2.5 Digital twins

Digital twins are getting more attention in recent years. Figure 2.9 presents the changes in the world-wide popularity of the phrase "Digital twin" in Google search engine [3].

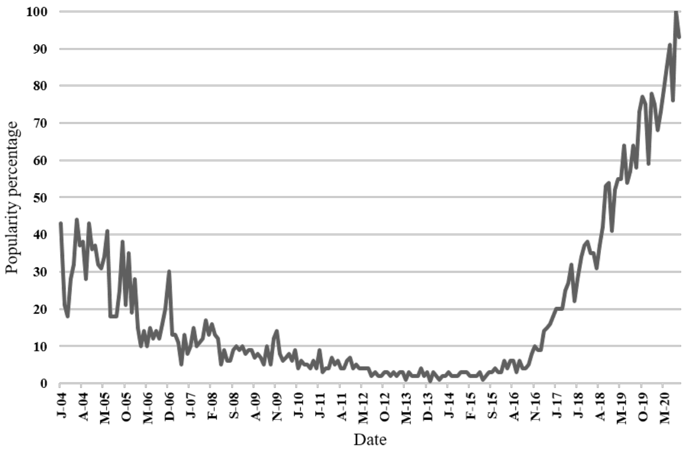


Figure 2.9: Popularity of digital twin in Google search engine from 2004 to 2020.

Despite the spread usage of the term "digital twin", definition of this term is not the same in all sources that have utilized it. Nevertheless, among these definitions, it seems to be a consensus that digital twins replicate a physical entity. A model, particularly in engineering, also replicates a physical entity. Therefore, it is crucial to clarify the differences between a model and a digital twin to avoid misusing them.

Wright and Davidson [Wright and Davidson, 2020] have defined the digital twins' updating process as their distinguishable characteristic from models. Accordingly, digital twins are proper for physical entities that change over time, and it is required to consider these changes. Lu et al. [Lu et al., 2020] have also identified the same characteristics to distinguish digital twins from models. Several studies [Tao et al., 2018] have identified being real-time data-driven also as a requirement for digital twins. However, what real-time update of the model means to depend on the purpose of utilizing the digital twin. Based on the definitions presented, it can be inferred that both digital twins and simulation models may represent a real-world phenomenon. However, digital twins are intended to simulate what is happening to their physical entity at a given time, while models can be manipulated to represent the general properties of a product in different scenarios. In other words, models can be a replication of the common properties among all individuals, but a digital twin represents only one entity.

[3] https://trends.google.com/

Kritzinger et al. [Kritzinger et al., 2018] have proposed an intermediate level between models and digital twins, namely digital shadows. Based on their classification, the criterion with which a category is defined is the type of data flow between the digital representation and the physical entity. A digital model is a digital representation of a physical entity when there is not data exchange between them. A digital shadow is when one of them is only receiver of data, and the other is always the data provider. Digital twins are models that both receive and provide data to and from the physical entity.

Several applications are found to benefit from utilizing digital twins. Manufacturing and life-cycle management of products are one of these applications. For life cycle management, digital twins can help the suppliers to adopt the processes through the new data they receive. Another application is in decision making during the product and production development [Bärring et al., 2020]. Maintenance costs and quality can significantly improve through use of digital twins [Bokrantz et al., 2020], and they can lead to more sustainable product and production processes [Pinzone et al., 2020].

An example of utilizing digital twins beyond engineering is in the medical sciences. This application is mainly through individualization and customization of medicines that can become available through digital twins [Siiskonen et al., 2020, Siiskonen, 2019].

Digital twins are expected to become the central area of focus in the context of geometry assurance, according to a survey conducted by Wärmefjord et al. [Wärmefjord et al., 2020]. The application of digital twins in manufacturing is mainly through the individualization of the production process for each product [Schleich et al., 2019]. Digital twins in this context are utilized to determine the optimal production processes' parameters by utilizing the data they receive from each product [Söderberg et al., 2017].

The individualization processes studied in this thesis claimed to be an application of digital twins. Variation simulation tools and models have been utilized in product and production processes. However, their application has been as simulation models as digital twins. The models are considered digital twins because of their correspondence with individual parts and assemblies, representing the assembly process for the unique entity they represent.

2.6 Optimization

Mathematical optimization is a branch of science that aims to find the best solution(s) among different alternatives. This research deals repeatedly with optimization problems and methods. Therefore, this section reviews the most relevant topics in this field. Section 2.6.1 defines optimization problems and their taxonomy. Section 2.6.2 reviews different optimization methods. Section 2.6.3 introduces GAs since they are utilized more often than are other optimization methods in this study.

2.6.1 Optimization problems

An optimization problem is a problem of finding the input of a function(s) among all feasible inputs so that the output is minimized. Equation 2.21 represents the mathematical formulation of this problem.

$$min f(\mathbf{x}) \tag{2.21}$$

Subject to:

$$g_i(\mathbf{x}) \leq 0$$

$$h_j(\mathbf{x}) = 0$$

In this problem, $f(x)$ is referred to as an objective function, $g(x)$ defines inequality constraints, and $h(x)$ represents the equality constraints of the problem. An optimization problem can lack constraints or have several.

There are different criteria with which to categorize optimization problems. Depending on the objective functions and constraints, the problem can be linear or non-linear. If one or several parameters is limited to integer values, the problem belongs to discrete problems or integer programming. Combinatorial optimization is another type of integer optimization problem whose goal is to find a set of objects from finite sets of objects that minimize the objective function.

If there is more than a single objective to be minimized, the problem is a multi-objective optimization problem. A multi-objective optimization problem can be converted into a single objective by using a weighted sum of all objectives if the priority of different objectives is known or if there is no priority among them. Nevertheless, sometimes it is preferred to have a variety of optimal solutions to select from them. Hence, a Pareto front can be generated that includes several solutions in which each solution is superior to other solutions in at least one objective. Figure 2.10presents a Pareto front for a two-objective optimization problem. In this figure, all Pareto front solutions are superior to other solutions in at least one objective. These solutions are distinguishable in the figure by a dashed curve that passes through them. There are different methods for obtaining Pareto front in multi-objective optimization. A comprehensive review of these methods is available in [Andersson, 2000].

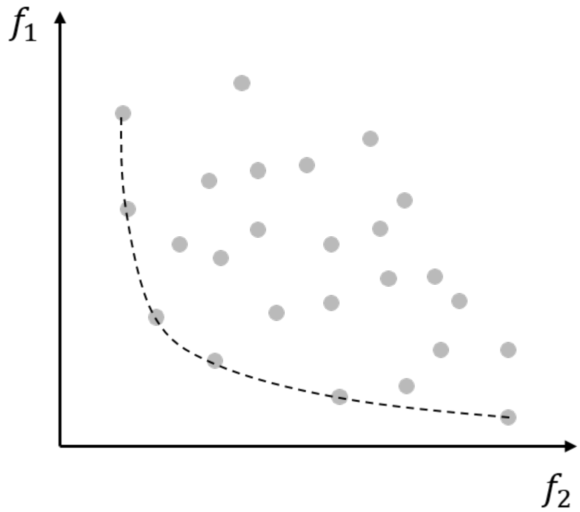


Figure 2.10: Pareto front in a two-objective optimization problem.

Figure 2.11 depicts some regular criteria for categorizing optimization problems and categories based on each criterion.

2.6.2 Optimization methods

The taxonomy of optimization methods[4] differs from the classification of the optimization problems. Figure 2.12 visualizes a common taxonomy of optimization algorithms. Optimization methods can be divided into the twin categories of deterministic and stochastic. Deterministic optimization methods do not utilize stochastic parameters. Hence, they are repeatable (i.e., always result in the same solution). Analytical and iterative methods guarantee one to find the global optimum solution within a specific tolerance, which is their main advantage. However, these optimization methods are confined to particular objective functions, constraints, and variables.

Analytical optimization methods are guaranteed to find the global optimal of the problem for a low calculation cost. Nevertheless, an optimization problem should pass three specific conditions to be analytically solvable. The variables of the problem should be continuous, and the objective function should be explicit and twice differentiable. Most practical engineering problems cannot satisfy these conditions.

[4]Different terminologies is used for this term. Optimization algorithms and optimization techniques are two other common phrases.

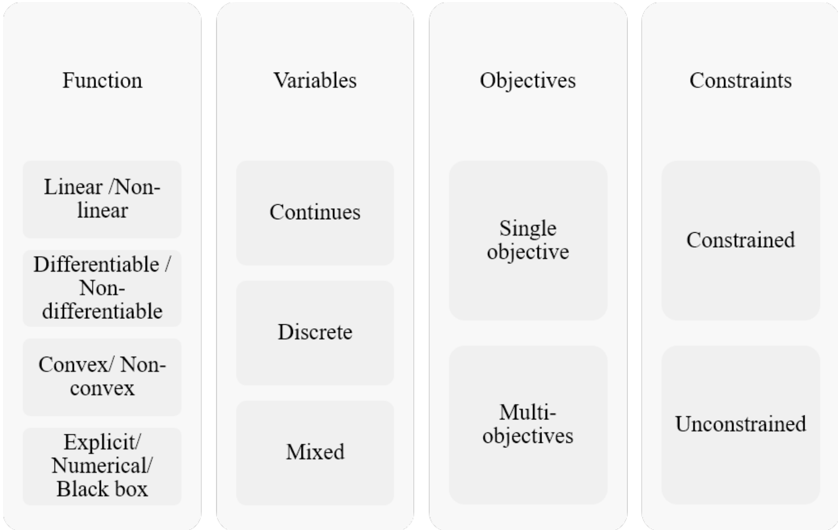


Figure 2.11: Different criteria for categorizing optimization problems.

To find the optimal solution of a problem analytically, the input values with which the first derivative of the objective function are zero should be found first ($f'(x_*) = 0$).). Among these values, those that make the second derivative greater than zero are optimal (f"$(x_*) > 0$). The global optimum solution is also the one that results in the lowest value of the objective. If the problem has more than one variable, instead of the first and second derivative, the gradient function and the Hessian should be utilized ($\nabla f(x_*) = 0$ and $H(x_*) > 0$).

Numerical methods are a category of optimization methods that do not utilize stochastic parameters. These methods can be utilized only for an unconstrained or bound constrained optimization problem. However, several methods convert a constrained problem to an unconstrained problem by reforming the constraints and adding them to the objective function. Generally, there is no guarantee that the solution that these methods find is the global optimum. The advantage of these methods is their low calculation cost. The general procedure of optimization in these methods is to check the value of the objective function in an initial interval and use different techniques to reduce the interval to converge upon the optimal solution.

Certain numerical methods do not utilize the gradient or the Hessian of the objective function. The golden ratio optimization method and the Bisection optimization method are two examples of this category. The other numerical methods that are more practical utilize the derivative function, Hessian, or an approximation of them to move more quickly toward the optimum solution. Gradient descent method, Newton method, and quasi-Newtown methods, including Davidon–Fletcher–Powell (DFP) and Broyden–Fletcher–Goldfarb–Shanno (BFGS), are most well-known algorithms in this category.

Another approach to deterministically find the global optimum of a problem is to utilize iterative methods. The main advantage of these methods is the same as those of the analytical method; they guarantee one to find the globally optimum solution of the problem, given a predefined tolerance. In the case of linear problems, the calculation cost is also relatively low. Consider a linear optimization problem (the objective function and constraints are linear) as presented by Equation 2.22.

$$min f(x_1, x_2) \tag{2.22}$$

Subject to:

$$g_i(x_1, x_2) \leq 0 \quad i = 1, 2, 3, 4, 5$$

The values of x_1 and x_2 that satisfy all constraints (i.e., those that are feasible) can be plotted as is depicted in Figure 2.13. The value of the objective function changes linearly among the points located inside this feasible area. Accordingly, the feasible point at which the objective function is minimum or

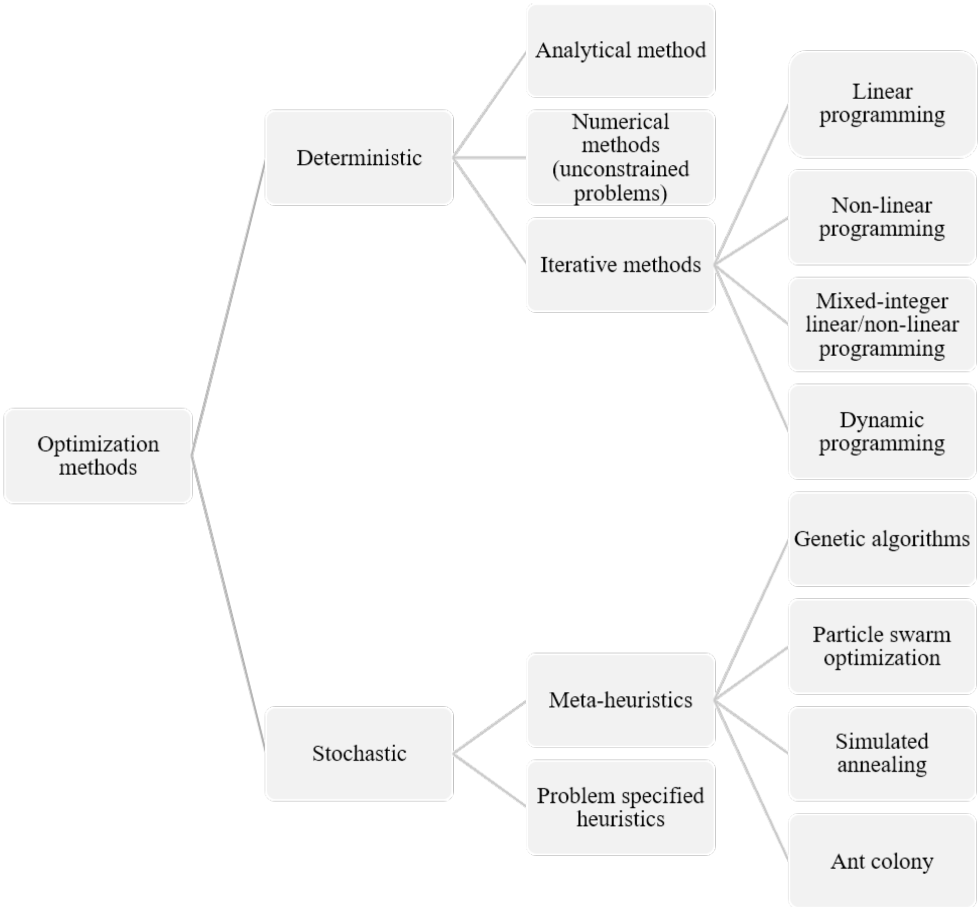


Figure 2.12: A classification of optimization methods.

maximum is one of the corners of this area. Thereby, to find the solution to these problems, the corners should be found first. Then, the value of the objective function can be evaluated to find the optimal solution. This procedure is the main approach in iterative optimization methods, particularly linear programming. Another approach is to utilize interior points of this feasible area to find the optimum solution.

Several methods are developed to avoid evaluating the value of the objective function for all the corners. These methods only go through the corners in which the value of the objective function decreases. The simplex method developed by Dantzig [Dantzig, 1961] is one of the most efficient methods in solving linear programming problems.

If the variables are limited to integer values, the problem can be solved for real values first (constraints relaxation). The solution can then utilized, in turn, to find an integer solution to the problem using branching methods. Branch and bound is one of the most common methods for this purpose. The linear optimization problems with integer variables are referred to as mixed-integer linear programming (MILP) problems, and MILP methods are used to solve them.

The iterative methods are further developed for non-linear programming (MLP) problems and mixed integer non-linear programming (MINLP) problems. However, the calculation cost and complexity of these methods are remarkably higher than those of the linear programming methods. Therefore, for large non-linear problems, these methods are not usually practical.

The convexity of the optimization problem is a crucial factor in iterative methods. Generally, an optimization problem is convex if any line segments between two points in the feasible region of the problem lie above the graph between the two points.

In convex optimization problems, there is either only one optimal solution (i.e., the global opti-

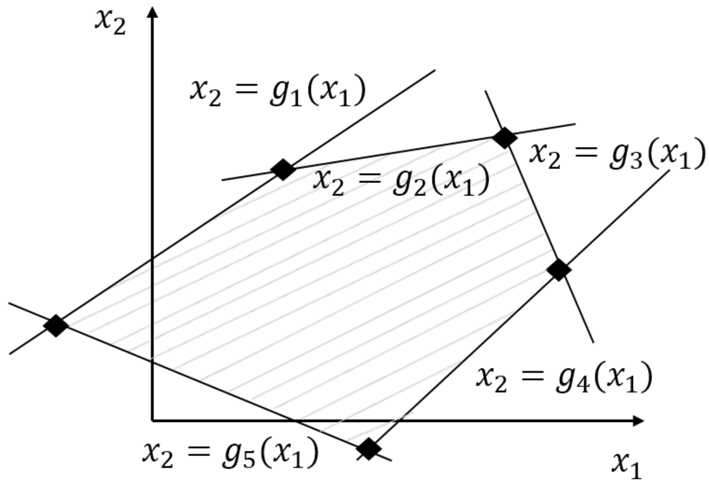


Figure 2.13: Concept of linear programing optimization method.

mum), or the problem has no solution. However, in non-convex problems, there might be more than one optimal solution. Therefore, in convex problems, the solution found through the iterative methods is guaranteed to be the global optimum. All linear optimization problems are convex. Therefore, linear programming can always guarantee that the result is the global optimum. However, in non-linear programming problems, if the problem is not convex, it can be very complex and sometimes impractical to identify the global optimum of the problem [Brinkhuis and Tikhomirov, 2005].

Stochastic optimization methods commonly utilize heuristics to solve the problem. Therefore, running them for the same problem with the same settings may not always result in the same solution. Moreover, finding the global optimum solution cannot be guaranteed in these methods (i.e., it is not clear whether the solution is global or local).

Metaheuristic algorithms are usually independent of the optimization problem, which is their main advantage and the reason for their popularity. These algorithms are commonly utilized to solve complex optimization problems that cannot be solved by other methods. Combinatorial optimizations, especially for relatively large problems, are an example of these complex problems. Although they cannot be guaranteed to find the global optimum, they can find sufficient solutions in a reasonable time with less complexity [Blum and Roli, 2003].

Except for simulated annealing (SA), most of the metaheuristics are nature-inspired. These algorithms can be divided into two categories: individual and population-based. In the population-based methods, a population of initial solutions is generated and improved gradually in each iteration. Therefore, they cover a relatively large design domain for the problem. Hence, there is a greater chance of finding the global optimum by utilizing these methods, although it comes at a higher calculation cost.

2.6.3 Genetic algorithms

A GA is an evolutionary algorithm from the category of metaheuristics. This algorithm is based on the Darwinian theory of evolution, where individuals evolve based on their fitness, and individuals with higher fitness have a greater chance of survival. Holland et al. [Holland et al., 1992] are pioneers who introduced GAs for mathematical optimizations. The overall procedure of this optimization algorithm and most of the other population-based evolutionary algorithms is to generate some random solutions to the problem and then improve them through exploration and exploitation. Figure 2.14 presents a schematic image of a general GA.

As shown in Figure 2.14, the first step is to generate the initial population. A population is a set of potential solutions to the problem. The initial population is commonly generated from random solutions so that the largest possible area of the design domain is covered. These solutions are referred to as

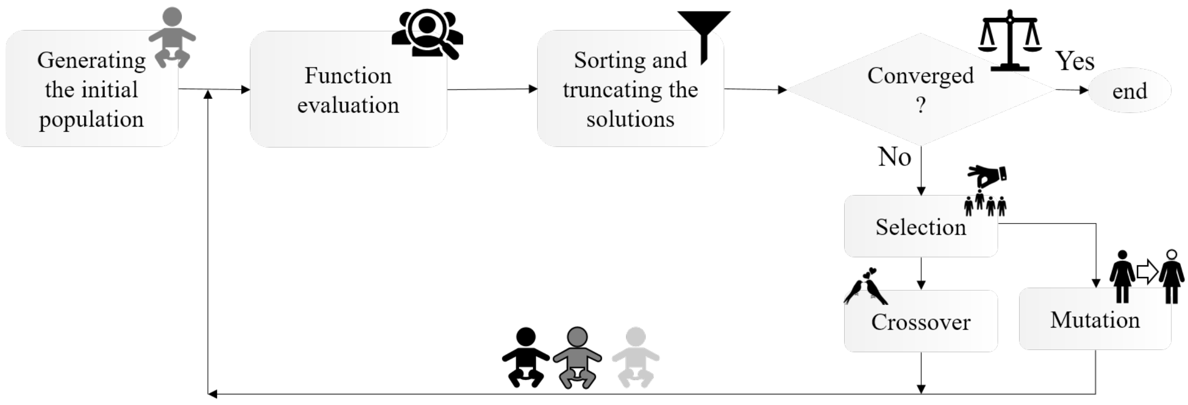


Figure 2.14: GA schematic.

chromosomes or individuals. In some problems, including read-coded GAs, the solutions generated in GA are the same as the real problem solutions (i.e., real numbers). However, this is not always the case, and sometimes the variables of the real problem are decoded to generate the GA solutions. For instance, to utilize binary GAs for real-number problems, the converted version of the variables from base 10 to base 2 is considered. Binary GAs are also commonly utilized to represent the existence and absence of a parameter in a model. The sequences can also be coded by integer values. The design domain of the problem is *phenotype*, and the design domain in the GA is *genotype*. The phenotype and genotype can be identical or different depending on the problem.

After calculating the objective of each solution using an objective function, fitness is allocated to the solution. In the next step, several solutions will be selected for generating new solutions. The selection is conducted by giving a higher probability of solutions with higher fitness. Thereafter, new solutions will be generated using genetic operators, including crossover and mutation. Thereby, solutions with the highest fitness among previous and new solutions create the next generation. Subsequently, solutions with lower fitness are removed from the new generation, and one iteration of the optimization is completed. This evolution procedure continues until the convergence criteria have been satisfied. An example of these convergence criteria is if the best solution does not improve after a specific number of iterations.

The primary GA presented by Holland [Holland et al., 1992] was a binary GA where the solutions could be only zero and one. However, due to the success of this algorithm, a variety of different GAs are developed, including real-coded GA, GA for sequencing and integer values, and GAs for multi-objective optimization problems. A well-known example of the GA for multi-objective optimizations is the non-dominated Sorting genetic algorithm (NSGAII) developed by Deb et al. [Deb et al., 2002].

Although the general procedure of all GAs is the same, depending on the type of the algorithm, different types of operators and tools can be employed to perform each task. Hence, a brief introduction to each task and associated method is presented in the following sections.

Initialization

The initialization phase is commonly conducted by generating random solutions in the feasible domain of the problem. There are several approaches to generate these solutions. One common approach is to generate random solutions so that the whole design domain is covered (i.e., the density of solutions is the same all over the design domain). Another approach is to utilize the design of experiments (DOE) methods to generate the initial solutions.

In some problems, knowledge of the problem can generate initial solutions that are more plausible. For instance, Tabar et al. [Sadeghi Tabar et al., 2019] developed a rule-based GA to optimize the sequence of welds based on this method. In this algorithm, a portion of the initial generation is created through previous knowledge of the importance of each weld. This approach results in a greater convergence rate for the problem.

Selection

A selection method should select the individuals in current generation to generate the next generation through genetic operators. In some versions of GA, the selection is conducted in two stages. First, a mating pool is generated by selecting individuals based on their fitness. Then, from that pool, the individuals are randomly selected to produce the next generation. The selection is performed in one stage by selecting the individuals based on their fitness in other versions. However, the methods that can be employed to select individuals based on their fitness are the same in both versions.

Several selection methods are presented for different types of GAs in the literature. A standard and straightforward method of selection in binary and real-coded GAs is proportional selection, or the roulette wheel method [Bäck, 1996]. In this method, the chance of selection for each individual corresponds to the fitness of that individual relative to other individuals' fitness values. If the problem is minimization, the fitness value should have a reverse relation with the objective (individuals with lower objective values receive greater fitness values). Equation 2.23 represents the formulation of determining the probability of each individual to be selected ($p(i)$). Accordingly, $0 < p(i) < 1$ and the sum of all $p(i)$s should be equal to one.

$$p(i) = \frac{fitness(i)}{\sum_{j=1}^{N} fitness(j)} \tag{2.23}$$

Tournament selection is another common strategy of selection in GAs. In this method, two or more individuals are randomly selected among all individuals. A tournament is then run among them, based on their fitness values, and the winner of the tournament is selected for the production of the next generation. Tournament selection also has several variants, depending on tournament size and how to define the tournament winner. This type of selection is commonly employed in multi-objective GAs. The ranking method and Genitor are two other methods of selection. Goldberg and Deb [Goldberg and Deb, 1991] present a comparison of these methods.

Crossover

The aim of conducting crossover operation is to exploit generations from individuals with greater fitness values. In the crossover, two selected solutions will generate two new solutions. Depending on the type of problem, different types of crossover may be applied. The solutions selected for this operation are referred to as parents, and the solutions generated are known as children. Figure 2.15 presents a crossover between two binary parents. Since the parents are divided at only one point, this crossover is a single-point crossover.

This operation is conducted in two steps. In the first step, the cutting location is defined randomly, and the chromosomes are divided into two sections from the cutting point. Then, each chromosome sweeps a section of it with the other chromosome. The result is two new chromosomes. This type of crossover can be conducted with more than one cutting point.

For real-coded GAs, where each solution is a real number or includes some real number, an arithmetical combination of each number can be utilized to conduct the crossover [Eshelman and Schaffer, 1993]. A sample of this combination is presented in the following relations where the generated individuals are indicated by r_{child1} and r_{child2}, and the individuals selected to perform the crossover are represented by $r_{parent1}$ and $r_{parent2}$. A random number between zero and one (ζ) is generated for each crossover operation.

$$r_{child1} = r_{parent1}\zeta + r_{parent2}(1-\zeta)$$
$$r_{child2} = r_{parent2}\zeta + r_{parent1}(1-\zeta)$$

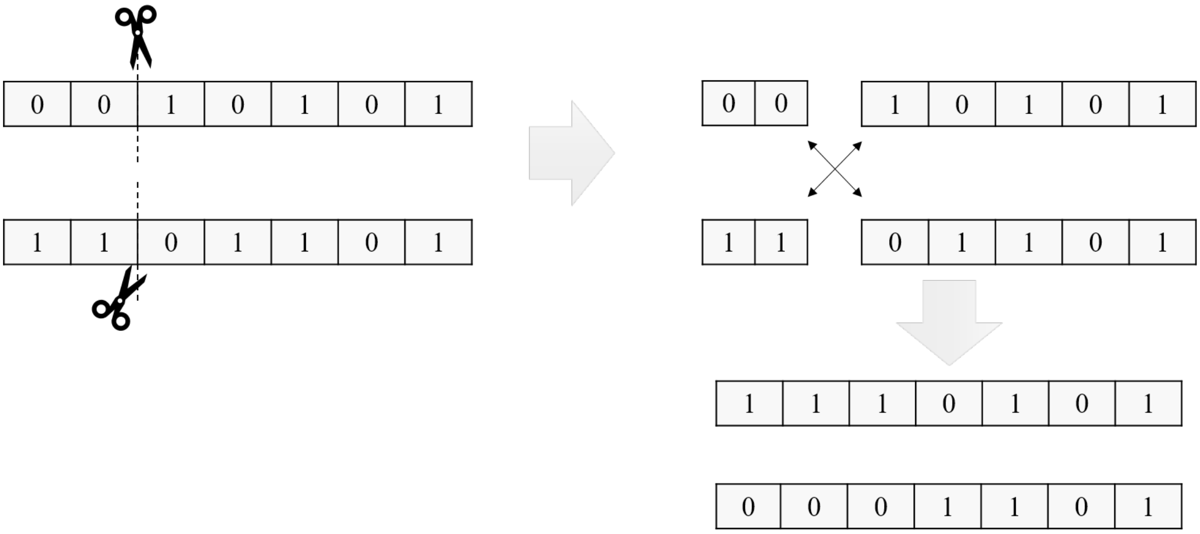


Figure 2.15: An example of a single-point crossover in a binary GA.

The crossover operation for sequencing GAs is more complicated than binary and real-coded crossovers. If the chromosomes that represent sequences are cut and swapped, as is performed in binary or integer crossover operations, one child may have the same integer two times, while the other child does not have it. Consequently, they do not represent sequences.

Several crossover operations are presented to solve this problem. One of these methods is the random keys crossover [Bean, 1994]. This method encodes the sequences to some random numbers between zero and one. Then, the crossover is applied to the random keys, and new solutions are generated. Thereby, the same coding is utilized to decode them. This procedure is explained with reference to a simple example. Consider the parents are 2 4 3 1 and 3 2 1 4. Firstly, two sets of random numbers are generated. The first set is 0.64, 0.95, 0.73, 0.28 and the second set is 0.33, 0.15, 0.08, 0.68. These random keys are sorted in an ascended order. The result is 0.28, 0.64, 0.73, 0.95, and 0.08, 0.15, 0.33, 0.68. The sequence of 2, 4, 3, 1 will be encoded so that each corresponding integer indicates the location of the random key in the encoded sequence. Thereby, the second position of the encoded sequence is 0.28, the fourth position will be 0.64, the third position is 0.73, and the first position is 0.95. Hence, the encoded sequence of 2, 4, 3, 1 is 0.95, 0.28, 0.73, 0.64. Using the same procedure, the sequence of 3, 2, 1, 4 will encode to 0.33, 0.15, 0.08, 0.68.

These encoded sequences can generate two new encoded sequences by a single point or multi-point crossover. For instance, if one point crossover is conducted, and the cutting point is after the second gene, the two new solutions will be 0.33, 0.15, 0.73, 0.64 and 0.95, 0.28, 0.08, 0.68. The next stage is to decode these new solutions to the sequences. In 0.33, 0.15, 0.73, 0.64, the smallest number is positioned in the second place. Therefore, the first integer of the decoded sequence is 2. The second smallest number (0.33) is located in the first position. Therefore the second integer of the decoded sequence is 1. Continuing the same procedure will result in 2, 1, 4, 3 and 3, 2, 4, 1.

Mutation

The aim of conducting a mutation operation is to explore generations to avoid converging the algorithm into locally optimal solutions. This operation is commonly performed by applying a random change to the solutions. In a binary GA, the mutation is conducted by selecting a random gene of the chromosome. If the value of the gene is 0, it will be changed to 1, and vice-versa.

In sequencing GAs, the mutation can be conducted by the swapping location of a random integer with the next integer. For instance, if the selected solution is 4, 3, 1, 2 and the selected gene for the mutation in this solution is the second gene, the mutated solution will be 4, 1, 3, 2. Another method of mutation for sequencing GAs is to select two random genes and sweep their locations.

Several methods can conduct the mutation operation for real-coded GAs. One method is to add or subtract a random real number inside the variables' limits to the solution. If the result is greater or less than the limits, the limits will substitute the solution. Otherwise, the result of summation or subtraction will replace the selected solution. Another method is to replace the selected solution with another random solution inside the limits of the corresponding variable [Goldberg, 1991].

Convergence criteria

A GA can have one or several condition(s) to stop the evolution process and represent the best solution among the last generation as the optimal solution. The selection of the convergence criteria depends on the goals of the optimization and the available resources, including time and computation power. The maximum number of iterations is commonly utilized as one criterion. Another criterion is to stop the algorithm if the best solution does not improve after a certain number of iterations. Considering a minimum range among all present solutions' fitness values in the current population is another criterion [Beasley et al., 1993].

CHAPTER 3

Research Approach

This chapter describes the research methodology utilized to conduct the research. Different stages of the research and methods of performing them are explained. The primary goal of this chapter is to clearly and simply present the research steps to support the evaluation and understanding of the research and its outcomes.

3.1 Research methodology

Utilizing a research methodology can provide a better understanding of the research and improve quality of the research. This improvement occurs is because the research process, goals, findings, and validation can be clarified in a structured way known by a larger number of researchers rather than only the researchers who are familiar with the research topic. Moreover, presenting a framework for planning, conducting, and validating the research can help the researcher reduce the risk of mistakes and problems occurring during the research. Hence, an established research methodology is utilized to carry out this research.

The research presented in the thesis relates to the context of design of production processes, the assembly process in particular. Design refers to a set of activities that result in producing and developing a product from a need, product idea, or technology [Blessing and Chakrabarti, 2009]. The product should fulfill stakeholder needs. The research in this thesis relates to developing production strategies that respond to the need to improve geometrical quality. If research provides understanding and supports to help improve the design practice or education, it belongs to the category of design research. Accordingly, this research can be categorized as design research.

Several methods claim to help to improve the quality of design research, including methodologies presented by Duffy, Andreasen, and O'Donnell [Duffy and Andreasen, 1995, Duffy and O'Donnell, 1999], the soft systems methodology of Checkland [Checkland, 1989], and the design research methodology (DRM) of Blessing [Blessing and Chakrabarti, 2009]. A detailed comparison of all these methodologies is presented by Blessing [Blessing and Chakrabarti, 2009]. These methods suggest more or less similar frameworks for conducting design research. Duffy, Andreasen, and O'Donnell are more focused on the research concerned with developing computer supports, and the Checkland method is proposed for action research approaches. The DRM is relatively more recent and tries to provide more generic solutions. This framework is widely used in design communities, particularly in the research group wherein this research is conducted.

The DRM is utilized to perform this research, based on the reasons mentioned earlier. The DRM is presented as a framework that includes four different stages to guarantee the quality of design research:

- *Research clarification (RC):* In this phase of the research, the two questions- "how is the current situation?" and "how is the desired situation?" should receive initial answers. The answers can be obtained by conducting an initial literature review. Then, the research questions will be designed based on these data. Besides, *success criteria* and *measurable success criteria* are required to be defined to evaluate the success of reaching the desired situation from the existing situation.

- *Descriptive study I (DSI):* In this phase of the research, the literature review is conducted meticulously to assess the current situation and to improve the initial understanding of the previous phase. Furthermore, the factors that may influence the current situation are clarified. Empirical studies may be performed, should a knowledge gap arise.
- *Prescriptive study (PS):* This phase aims to develop tools and methods to improve the current situation and to approach the desired situation.
- *Descriptive study II (DSII):* This phase of the research aims to evaluate the improvements presented in the previous phase by measuring success criteria. As a result, it will be clarified whether the intended improvements are achievable by the presented methods or tools.

A research study needs neither to include all four phases nor to follow them in sequential order. It is encouraged to iterate different phases to further improve the outcomes through the updated findings of each phase. Figure 3.1 presents a schematic process for using these phases in design research.

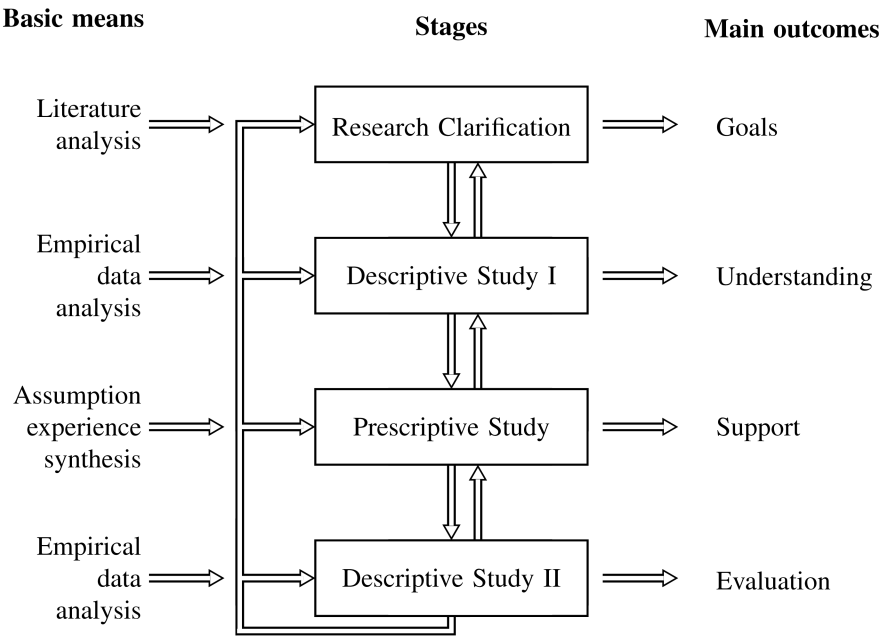


Figure 3.1: Design research methodology (DRM) by Blessing and Chakrabarti [Blessing and Chakrabarti, 2009].

3.2 Research framework based on the DRM

This section presents the research process in the DRM framework to clarify the process by which this research is conducted.

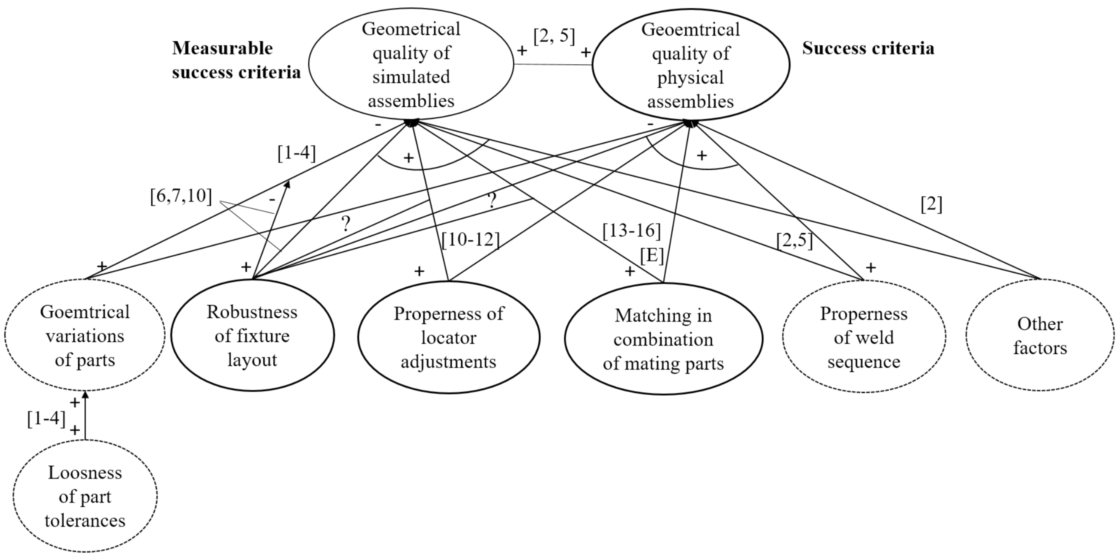
3.2.1 Research clarification

The ultimate goal of this research is to present potential geometrical improvements of physical assemblies through individualization. Therefore, the success criteria can be defined as improvements in the geometrical quality of physical assemblies. Nevertheless, the improvements in physical assemblies' geometrical quality cannot be evaluated, due to scope of the research. However, using computer simulations, the geometrical quality of computer models representing physical assemblies can be measured.

Hence, the measurable success criteria are improvements in the geometrical quality of the computer models that represent physical assemblies.

Arguably, not every improvement in geometrical quality is worth the cost of individualizing the assembly process. Individualization may demand additional time and resources for the assembly process. Hence, the desired situation is when the gains of individualization are noticeably more significant than the losses. Accordingly, these constraints should also be included in the success criteria of the products. However, the goal of this research is not to prove whether individualization is reasonable. The main goal is to evaluate the potential of individualization in improving the geometrical quality of assemblies. The costs and gains of individualization are subjective matters that depend on the target industry and on the available technologies. Nevertheless, based on recent advances in scanning the part deformations and robotized production lines, this method is more accessible now than in previous decades.

Notably, success criteria may not evaluate the success of the research conducted, but instead, one of its outcomes that the presented supports (i.e. the tools and methods). A reference model is developed in which the influential factors on the geometrical quality of sheet metal assemblies are defined to understand the existing situation. This model is improved by acquiring more knowledge about the influential factors in other research stages, particularly DSI. A simple method for the graphical representation of reference and target model is developed by Blessing and Chakrabarti [Blessing and Chakrabarti, 2009] that is also utilized in this research to represent these models. Figure 3.2 presents the final reference model based on this representation method.



1- [Söderberg and Carlsson 1999], 2- [Söderberg *et al.* 2006], 3- [Tronthon 2004], 4- [Chase and Parkinson, 1991], 5- [Wärmefjord *et al.* 2016], 6- [Camelio *et al.* 2003], 7- [Camelio *et al.* 2004], 8- [Shah *et al.*, 2007], 9- [Hong and Chang, 2002], 10- [Germer *et al.*, 2014], 11-[Beckmann *et al.,* 2015], 12- [Keller, 2014], 13- [Mansor, 1961], 14- [Fang and Zhang, 1995], 15-[Chan and Linn, 1999], 16- [Kannan et al., 2009]

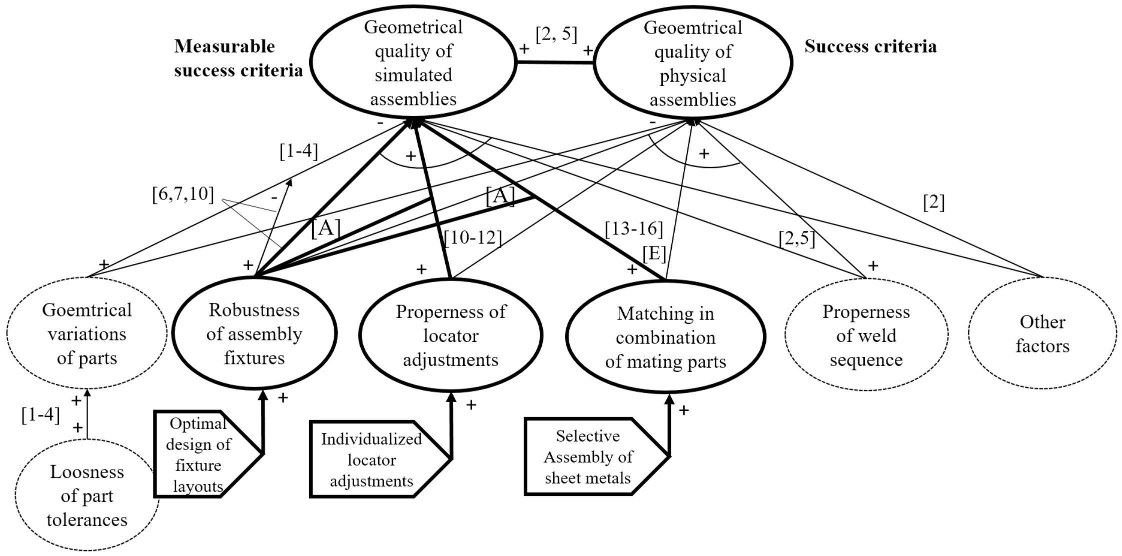
Figure 3.2: The reference model.

This model represents the relations among different factors that can influence the measurable success criteria and the success criteria. A factor is an aspect of the existing situation that can influence other aspects. For instance, the geometrical variations of parts or the robustness of fixtures are factors that can affect the geometrical quality of assemblies. Each factor should be formulated as an **attribute** of an **element** to avoid ambiguity. For example, the fixture alone cannot be considered a factor. Robustness is a fixture attribute that can be assessed. Therefore, the robustness of fixtures is considered a factor.

Links indicate the relation between these factors. The links with arrows indicate causal relationships. Each link has two signs, one at each end. The plus (+) sign indicates the related factor is increasing, and the minus (-) sign represents a reduction in the relevant attribute of the factor. For instance, increasing geometrical variations of parts will reduce the geometrical quality of the simulated assemblies. The relationships between every two factors may not be symmetrical (i.e., each link presents the relation only in one direction). For the previous example, with an increase of geometrical variation among parts, the geometrical quality of the simulated assemblies reduces. This link does not mean reducing the geometrical quality of simulated assemblies will result in increasing part variations.

In this model, both signs at the ends of each link can be reversed together (+ to - and - to +). In the previous example, changing the signs indicates that reducing the amount of part variation will increase the geometrical quality of the simulated assemblies. An arc between several links indicates they have the same sign toward the connected factor. The source of each connection presented is indicated in brackets. A question mark indicates the relation is unknown and could not be found in available studies. The letter A indicates the relation is assumed to exist, and the letter E indicates the relation is expected to exist by stakeholders of the research. The relations found by previous studies are indicated by the reference study that evidences them. Dashed lines depict the factors that are outside of the scope of this research.

The desired situation is to improve the geometrical quality of assemblies through individualization. Furthermore, based on previous knowledge, it is assumed that fixtures' robustness can directly influence potential improvements by locators adjustments and selective assembly. Hence, this factor should be under control. The desired situation is depicted in an impact model (see Figure 3.3).



1- [Söderberg and Carlsson 1999], 2- [Söderberg *et al.* 2006], 3- [Tronthon 2004], 4- [Chase and Parkinson, 1991], 5- [Wärmefjord *et al.* 2016], 6- [Camelio *et al.* 2003], 7- [Camelio *et al.* 2004], 8- [Shah *et al.*, 2007], 9- [Hong and Chang, 2002], 10- [Germer *et al.*, 2014], 11-[Beckmann *et al.,* 2015], 12- [Keller, 2014], 13- [Mansor, 1961], 14- [Fang and Zhang, 1995], 15-[Chan and Linn, 1999], 16- [Kannan et al., 2009]

Figure 3.3: The initial impact model.

The research questions are formed to clarify how the desired situation can be achieved from the existing situation. The first research question clarifies how a selective assembly technique can be utilized in sheet metal assemblies. The second research question focuses on the relationship between individualization and quality of locator adjustments. In other words, this question regards whether individualizing the locator adjustments improves the fit of locator adjustments and, therefore, the geometrical quality, and how this individualization can be conducted. The result of locator adjustments and part combination might be affected if both of these factors are modified simultaneously. Therefore, the third research question is designed to address this matter (i.e., interaction between these factors). The fixture layout might affect the relationship between the geometrical quality and fit of part combinations and locator adjustments. Hence, the fourth research question is designed to address this issue.

The DRM divides the design of the research into seven different categories, based on the types of studies carried out in each research stage. Each stage can be review-based, comprehensive, or initial. A review-based stage is conducted by collecting the knowledge that others have provided mainly through literature review. A stage is comprehensive if the research accomplishes a contribution in the outcome of that stage. The contribution in descriptive results is to discover novel information about the situation. A comprehensive prescription is to develop a new method or tool. This research belongs to the category in which RC is review-based, DSI and PSI are comprehensive, and an initial DSII is also conducted.

3.2.2 Descriptive Study I

This phase of the study has been carried out in several iterations. In the first iteration, the reference model presented by Figure 3.2, the success criteria and measurable success criteria are finalized by performing literature reviews of the related contexts (e.g., selective assembly, locator adjustments, and fixture layout design). The results presented in Section 3.2.1 emerge from both RC and the first iteration of DSI. The first iteration of DSI has been mainly review-based.

Defining the existing gaps required to be addressed in this research is also performed in the first iteration of DSI. The first gap was that the selective assembly technique is not developed for the sheet metal assemblies. The second gap is that individualization has not been studied in locator adjustments. The third gap was that there is no comprehensive method of defining the optimal fixture layout to maximize the robustness. Subsequently, the effects of fixture layout on individualization and the possibility of accumulating the improvements are the research gaps that are not addressed in existing studies and should be addressed in this research.

Among the research gaps, some are related to developing a tool or method (prescriptive), and some are about discovering the relations or the links between different factors (descriptive). The former category is addressed in the PSI, and the latter is addressed in the second iteration of the DSI.

The second iteration of DSI has been carried out by performing experiments using the developed tools and methods in PSI. Accordingly, the research has contributed to this phase by discovering relations among several factors. These contributions are presented in Papers D and F. The method of establishing these relationships is based on induction reasoning. In both papers D and F, several sample cases are used to conduct experiments. Thereafter, the results of these experiments are generalized to a category of products. The validity results obtained by this method are discussed in Section 5.4.1.

3.2.3 Prescriptive Study I

In the prescriptive phase of the study, new methods and tools are presented to cover the defined gaps and to improve the products' success, here identified as the geometrical quality of assemblies. The methods are a sequence of actions prescribed in each paper to fulfill the success criteria. The tools are codes and programs developed to implement the methods.

Papers A and B present support to conduct selective assembly for sheet metals. Paper B is presented to address a gap discovered by presenting the methods and tools of paper A. Papers C addresses the research gap about the individualization of locator adjustments by presenting a method of individualization of locator adjustments. The defined research gap in the optimal design of fixture layouts for compliant sheet metal assemblies is also addressed in paper F.

3.2.4 Descriptive Study II

DSII can be conducted at two different levels, initial and comprehensive. A DSII phase is comprehensive if the method and tools presented are evaluated during the entire life cycle of product in the long term. It is initial if the supports presented are evaluated on a smaller scale. Accordingly, the time and scope of this research allows only an initial DSII of the supports presented. This DSII is conducted for all methods and tools presented in this research by applying them in several sample cases. This application is performed through simulations.

Figure 3.4 lists the distribution of papers on different phases and research questions.

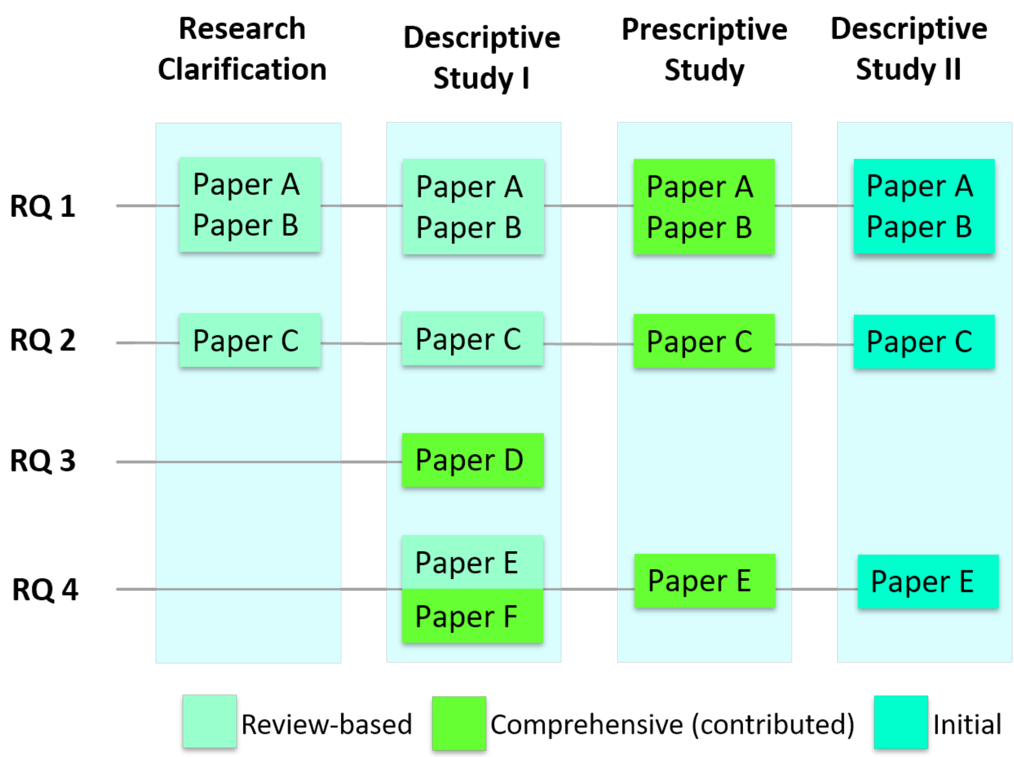


Figure 3.4: The distribution of Paper A-E in the context of the DRM.

3.3 Utilized methods

Different methods are utilized in each phase of the research to achieve the goals of that phase. These methods are reviewed in this section.

3.3.1 Field studies

Field studies or field research is a method of data collection that encompasses various approaches to collect raw data outside a laboratory. These approaches include but are not limited to observations, informal interviews, working in a workshop, living among some people, and so forth [Burgess, 1984].

The field studies performed in this research comprise mainly the visits to the production lines of the automotive industries in Sweden and Japan. More than 20 production sites were visited to get an overview of real production and assembly workshops. Videos were recorded during these visits, although none of these videos can be published. Moreover, some informal interviews with the design and production engineers were carried out during these visits.

These studies' main goal was to keep the researcher as close as possible to reality and to get an idea of what happens in the industry. Hence, the researcher could, to some extent, determine how published academic works compare with industrial practice.

An advantage of this method of obtaining data in research is the freedom that the researcher has to observe and discover new insights (i.e., outside of predefined questions). On the other hand, the observation might become so general that no clear outcome can be specified as a result. Moreover, there is a risk of becoming biased because of meeting only some people or observing only some parts of the phenomenon.

3.3.2 Literature studies

The literature study is the primary method used to analyze the existing situation and methods of individualization to improve the geometrical quality. Accordingly, in all papers, the literature analysis is performed to understand the current situation, clarify the existing gap, and position the tools and methods presented.

Literature studies are crucial for research because they avoid redundancy between studies. They help the researcher to gain a deep understanding of the research subject. On the other hand, getting too deep into the subject through literature studies might limit the perspective of the researcher those of previous researchers.

3.3.3 Experiment

An experiment is a procedure designed to validate, reject, or support a hypothesis. Based on the definition by Blessing and Chakrabarti [Blessing and Chakrabarti, 2009], an experiment should satisfy the following criteria:

- The researcher has control over independent parameters subjected to the experiment.
- Participants or objects are randomly assigned to groups.
- Participants or objects can be considered representatives of the target population.

The experiments conducted in this research are performed using simulations. The inputs of simulation models are manipulated, and the changes in the outcomes of simulations are observed. In papers where the main contribution is prescriptive, experiments are utilized to test whether the methods presented fulfill their goals. Experiments in means of simulations are also conducted in descriptive studies to discover the relations among different factors.

A primary advantage of using experiments in research is the capability of this method to discover causality among factors relative to the other factor. The factors can be controlled in an experiment. Therefore, one can observe how changing one specific factor in a time can influence an outcome. This control may not exist in other methods, including case study and observation. On the other hand, the experiments are commonly conducted in laboratories where all factors, including the environment, are controlled. Therefore, the same results might not be achieved when the phenomenon is happening in an environment where factors not foreseen may influence the outcome. It is also essential to consider the influence of interaction among each factor. The influence of a factor on the outcome may depend on the other factors' status.

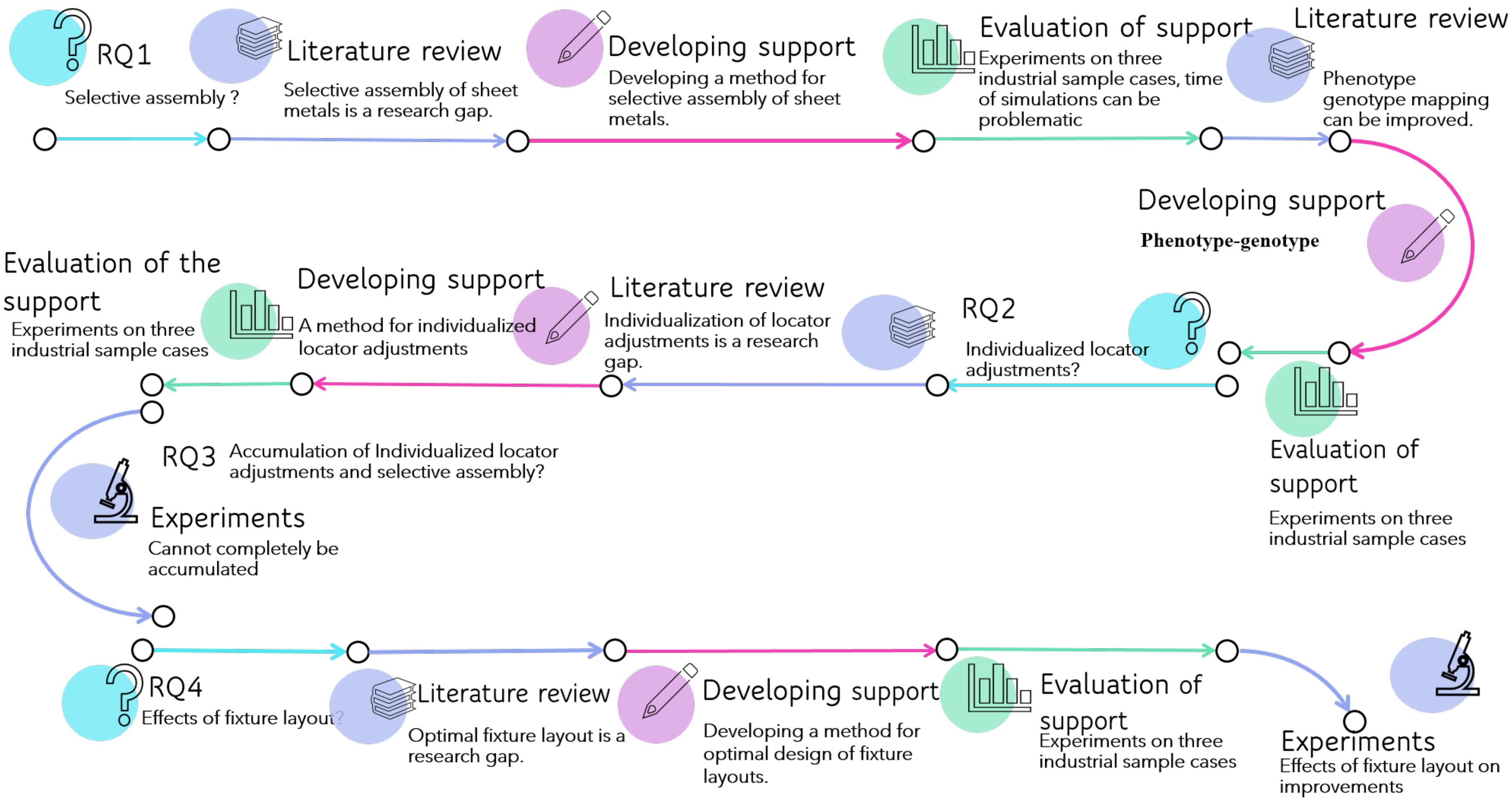


Figure 3.5: The sequence of conducting different tasks for each research questions.

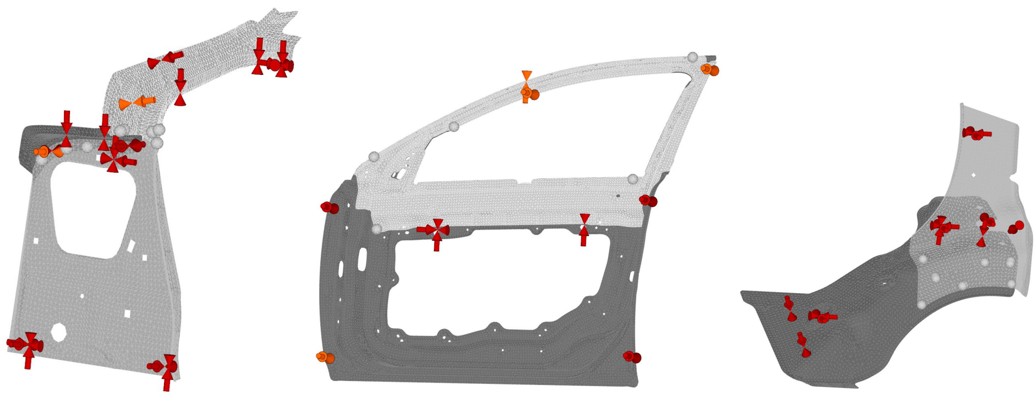
CHAPTER 4

Results

This chapter introduces the utilized sample cases and summarizes the results of the research that also form the basis of the appended papers. The interconnections of the results are also clarified in this chapter.

4.1 Sample cases

This research has utilized three industrial sample cases to evaluate the prescriptive results and determine the descriptive results. These cases are computer models of physical assemblies from the automotive and aerospace industries.



(a) Sample case 1 (b) Sample case 2 (c) Sample case 3

Figure 4.1: The utilized sample cases in the research.

Figure 4.1 displays the models of the three sample cases generated in RD&T. The arrows in each case indicate a locking direction by a locator. The white spheres represent the spot-welds.

4.2 Paper A: Selective assembly of sheet metals

The target dimensions in some assemblies, including piston cylinders or bearings, are simply a linear function of some dimensions of their parts. These types of assemblies are referred to as *linear assemblies* in this thesis. The literature suggests that the previous methods and applications of selective assembly are limited to linear assemblies. This technique is utilized only in assemblies where the tolerances of target dimensions are so tight that it is unreasonable to tighten parts' tolerances.

New production lines have more automation. Moreover, more inspection data are available. For instance, the deformed shapes of the produced parts can be determined by the photogrammetry technique [Bergström et al., 2018]. It is reasonable to take advantage of these availabilities by applying the selective assembly technique to sheet metal assemblies, which are the dominant type of assembly in the automotive and aerospace industries. Xing and Wang [Xing and Wang, 2018] claim that they developed a selective assembly technique for sheet metal assemblies. However, they had not considered contact modeling in the simulation of the assembly procedure of sheet metals. Hence, they obtained a linear relationship between part variation in welding points and the variation of inspection points in the assembly. Nevertheless, the relation in real sheet metal assemblies is not linear, due to the contact between parts. Consequently, their model does not apply to real sheet metal assemblies.

Paper A addresses this gap and tries to fill it by presenting a new selective assembly technique for sheet metals. In the selective assembly of linear assemblies, the assembly characteristics can be improved by matching several parts' characteristics. However, in sheet metal assemblies, the parameters that control characteristics of the assembly are numerous. The deviations in most areas in each part, the mechanical properties of each part, part variation, and production process variations are among the contributing factors. Consequently, the preliminary question that this paper should answer is as follows: Is it possible to improve the geometrical quality of sheet metal assemblies through a selective assembly technique?

Three main differences arise between sheet metal assemblies and linear assemblies. The first difference is that in sheet metals, in addition to the variation, the mean deviation of dimensions also varies with changes in the combination of parts. As a result, the optimization should be performed for two objectives instead of one. The second difference is the lack of a criterion to divide the parts into groups. In linear assemblies, parts can be divided into groups based on their measured dimensions. However, in sheet metals, the geometrical quality of an assembly cannot correspond to only one or several dimensions from parts. Accordingly, the grouping cannot be applied to sheet metals, and the matching should be conducted for individual assemblies. The third difference is that the final geometrical quality of sheet metals cannot be calculated by a summation or subtraction of some dimensions of parts. Instead, the assembly process should be simulated using CAT programs.

The method presented for the selective assembly of sheet metals is applied to the sample cases for evaluation. Three batch sizes of 25, 50, and 100 are selected for each case to evaluate the effect of batch size on the improvements. Pareto fronts are obtained, and the percentage of improvements is calculated for every case and each batch size compared to the average RMS_v and RMS_m of 1000 random combinations.

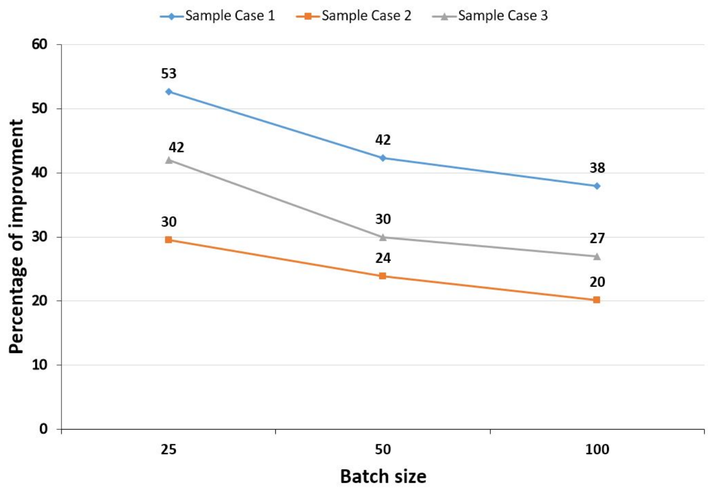


Figure 4.2: Effect of batch size on RMS_v [Rezaei Aderiani et al., 2019a].

Based on the results, both RMS_v and RMS_m have improved for all cases. Hence, the answer to the question of the possibility of improving the geometrical quality of sheet metals is positive. Figures 4.3 and 4.2 visualize the effect of batch size on RMS_m and RMS_v, respectively. The percentage of

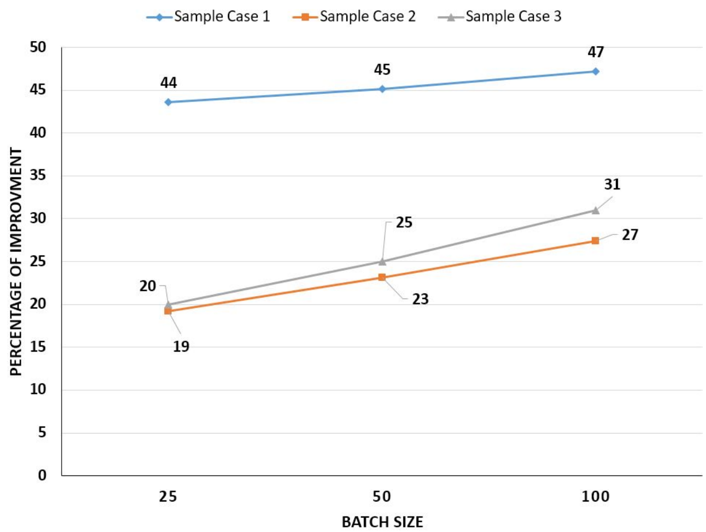


Figure 4.3: Effect of batch size on RMS_m [Rezaei Aderiani et al., 2019a].

improvement of RMS_m is greater for larger batch sizes, whereas it is the opposite for RMS_v.

4.3 Paper B: Improving the convergence rate in selective assembly

The results of Paper A indicate that by growing the size of the problem, it is more reasonable to utilize evolutionary optimization algorithms, including GA, to find the optimal combination of parts. These optimization algorithms have already been used to find the optimal combination of parts in the selective assembly technique. However, Paper B illustrates that the coding utilized to map phenotype to genotype is not a one-to-one mapping. Consequently, it may affect the convergence rate and calculation costs of the optimization process.

One-to-one mapping is presented in Paper B to evaluate the effect of the existing mapping. Subsequently, both mapping methods are applied to a linear assembly and two sheet metal assemblies. Since the population size is a crucial factor in the convergence rate, the optimization is performed for four different population sizes of 50, 100, 250, and 500 for each case. Moreover, each experiment is replicated 100 times, and the average is considered to nullify the effects of stochastic parameters. The mean number of function evaluations is considered an indicator of the convergence rate of the optimization for each mapping method.

Figure 4.4 presents the percentage of improvements achieved by the new method of mapping for each sample case and population size. These improvements indicate the percentage of reduction in the mean number function evaluations.

Based on the results, using the new method leads to better solutions (more significant improvement in geometrical quality) on the average. In other words, the optimization algorithm performs better with the new method.

4.4 Paper C: Individualizing locator adjustments of assembly fixtures

Paper C of this thesis focuses on the individualization of the second technique, locator adjustments. Based on the literature studies in Paper C, studying individualized adjustments for compliant assemblies is a research gap. Thus, the results of both individualized locator adjustments and non-individualized locator adjustments should be evaluated and compared. The non-individualized locator adjustments means employ the same adjustments to produce the entire batch of assemblies (i.e. adjusting the locators

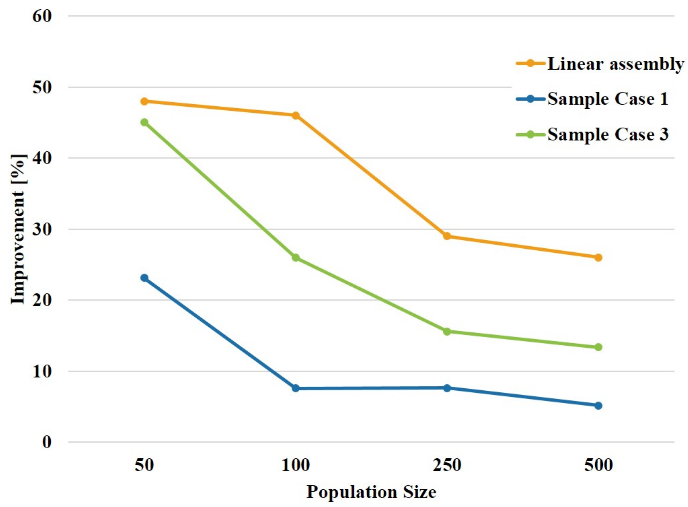


Figure 4.4: The percentages of improvements in convergence rate (the mean number of function evaluations) in each sample case [Rezaei Aderiani et al., 2020b].

only once for the whole batch). Individualized adjustments, however, required one to adjust the locators for each individual assembly based on the non-ideal geometry of the parts used for that assembly. Therefore, two methods are developed in this paper, one for non-individualized adjustments and one for individualized adjustments. The goal is to minimize the *RMS* of deviation of all nodes. The objective of non-individualized adjustment is to minimize the mean deviation of all assemblies RMS_m. Two constraints are added to avoid undesired plastic deformations and residual stresses by limiting these parameters during assembly.

The methods are applied to the three sample cases, and the results are evaluated. The geometrical quality of each individual assembly and all assemblies together are presented to compare individualized and non-individualized adjustments. The criterion for the former is RMS_d, and the criteria for the latter are RMS_m and RMS_v. Figures 4.5, 4.6, and 4.7 present the RMS_d of each assembly for sample cases 1, 2, and 3, respectively. Since the individualized adjustments are applicable when a digital twin is generated for each assembly, the results in these charts are classified based on use of a digital twin or not.

All assemblies have better geometrical quality when individualized adjustments are applied than when non-individualized adjustments are implemented. Furthermore, non-individualized adjustments have reduced the geometrical quality of some assemblies though the quality, on average, has been improved.

Table 4.1 lists the RMS_v and RMS_m of the whole batch of assemblies and the percentage of improvements for both individualized and non-individualized adjustments.

The percentage of improvements illustrates that employing individualized adjustment improves the geometrical quality considerably over non-individualized adjustments. Paper C also presents a modification of the optimization algorithm that reduces the required adjustments for the same improvements.

4.5 Paper D: Combining selective assembly and individual locator adjustments

The selective assembly and individualized locator adjustments are promising in the geometrical quality improvements of the assemblies. Nonetheless, is it possible to have even more significant improvements by simultaneously employing both techniques in a smart assembly line? Paper D investigates the answer to this question by examining the improvements gained from combining these two techniques and

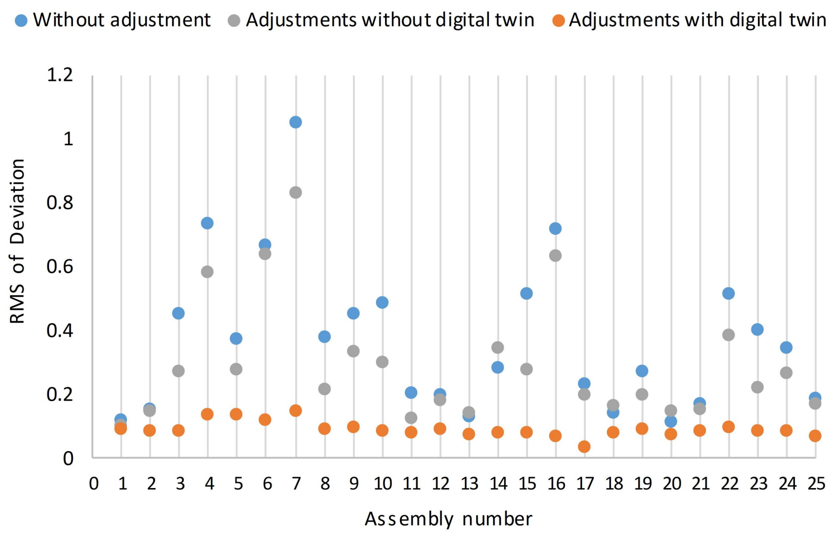


Figure 4.5: RMS_d of individual assemblies without adjustments, with non-individualized adjustments and with individualized adjustments for the first sample case [Rezaei Aderiani et al., 2019b].

Table 4.1: *RMS* of variation and mean deviation of batch of assemblies without adjustments, with non-individualized adjustments and with individualized adjustments

Case	Quality criteria	Without adjustments	Without digital twin		With digital twin	
				[%]		[%]
1	RMS_v	1.53	1.22	20	0.29	81
	RMS_m	0.36	0.27	25	0.08	78
2	RMS_v	1.19	1.11	7	0.55	54
	RMS_m	0.32	0.27	16	0.16	50
3	RMS_v	1.42	1.08	24	0.46	68
	RMS_m	0.29	0.24	17	0.11	62

comparing them with when they are employed separately.

Table 4.2 presents the achieved improvements resulting from three possible scenarios on three different sample cases. Scenarios 1 and 2 represent the application of only selective assembly and only individualized locator adjustments, respectively. The third scenario represents the results of combining both techniques. The combination is achieved by applying first the selective assembly and second the individualized locator adjustments.

The results evidence that combining the techniques may result in further improvements than applying only individual locator adjustments for the utilized sample cases. However, the improvements gained through the combination might not be notable.

The possibility of improving a parameter through optimization is because of the sensitivity of the function to its input parameter. Accordingly, when the assemblies' geometrical quality can be improved by selective assembly and individualized locator adjustments, the quality is sensitive to the part combination and locator adjustments. Hence, based on the results determined in Table 4.2, the sensitivity of the assembly quality to the part combination should reduce if individualized locator adjustment is applied. Therefore, a sensitivity analysis of the geometrical quality of part combinations with and without applying individualized locator adjustments can validate the results.

The assemblies' sensitivity to 10 random part combinations is evaluated for the sample cases with and without applying individualized locator adjustments. Figures 4.8 and 4.9 depict the results of this

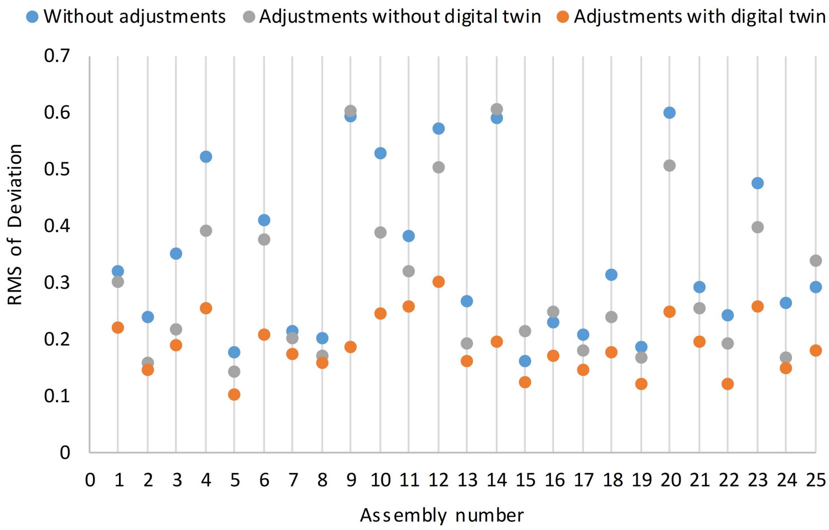


Figure 4.6: RMS_d of individual assemblies without adjustments, with non-individualized adjustments and with individualized adjustments for the second sample case [Rezaei Aderiani et al., 2019b].

Table 4.2: RMS_v and RMS_m before and after applying different scenarios [Rezaei Aderiani et al., 2020c].

Case	Criteria	Without improvements	Different scenarios					
			1	2	3	1 [%]	2 [%]	3 [%]
1	RMS_v	1.68	0.85	0.29	0.3	49	83	83
	RMS_m	0.39	0.24	0.08	0.08	38	77	77
2	RMS_v	1.07	0.78	0.57	0.50	27	46	53
	RMS_m	0.30	0.25	0.17	0.16	18	43	46
3	RMS_v	1.12	0.76	0.47	0.44	32	58	61
	RMS_m	0.26	0.21	0.12	0.11	19	53	57

evaluation for RMS_v and RMS_m, respectively.

The results presented in Figures 4.8 and 4.9 confirm the formulated hypothesis from the results of Table 4.2. Accordingly, in assemblies for which individualized locator adjustments are employed, the sensitivity to part combination is significantly reduced. Hence, in these cases, employing selective assembly in addition to locator adjustments may not result in notable additional improvements.

4.6 Paper E: A new method for the optimal design of fixture layouts

The utilized fixture layout to perform the assembly procedure is a critical factor in achievable geometrical improvements by selective assembly and individualized locator adjustments. Therefore, to gain better control over achievable improvements, particularly in the design stage, these effects should be clarified. This clarification can be achieved by employing different design strategies of fixture layouts and evaluating the achievable improvements. However, the literature review of this paper demonstrates that a well-established design method of fixture layouts, particularly for compliant sheet metal assemblies, is missing. As a result, this paper addresses this research gap by presenting a new method of designing fixture layouts.

The objective is to present a fixture layout design method to achieve the highest geometrical quality of assemblies (i.e., minimize the effect of input variations, particularly part variations). The design parameters are the location and type of each locator with respect to the constraints.

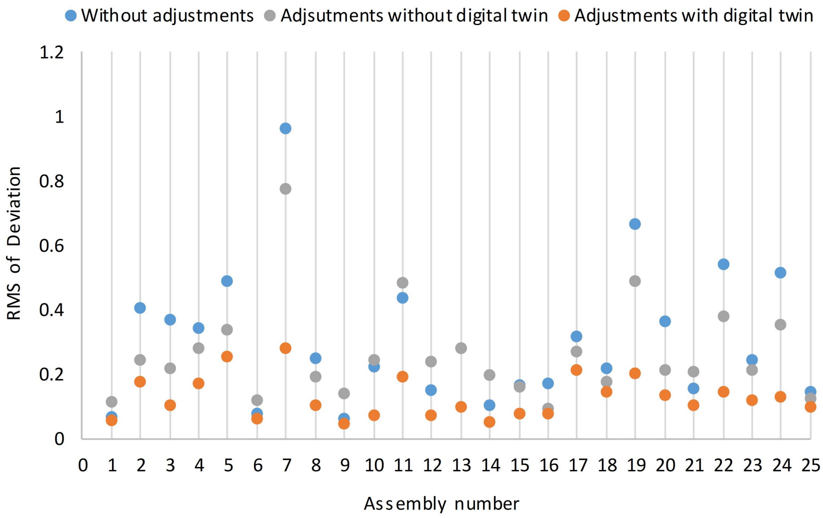


Figure 4.7: RMS_d of individual assemblies without adjustments, with non-individualized adjustments and with individualized adjustments for the third sample case [Rezaei Aderiani et al., 2019b].

The method presented in this paper is conducted over three main stages. In the first stage, the feasible areas of parts to be a locating area are defined. Then, these areas are divided into smaller areas to form the design space of the problem. Thereby, the sizable continuous design domain is converted to a smaller, discrete design domain. As a result, the optimization becomes more practical. In the second stage, the optimal locating areas among all these areas, and the optimal locator type in each area is determined. In the third stage, the locating position in each area is further improved. Figure 4.10 illustrates the overall procedure of the method presented in this paper.

The evaluation of this method is conducted by applying it to two sample cases. The optimal fixture layout for each sample case is determined. Hence, the geometrical qualities of assemblies with optimal fixture layouts are compared with the quality of the assemblies produced by the existing fixture layouts (i.e. the fixtures that are used to produce these assemblies in the industry). This comparison manifests the superiority of the presented method in the design of a fixture layout. The improvements in the variations achieved by utilizing the new optimal fixture layouts are 57% and 23% for the first and the second sample cases, respectively. This paper also presents a top-down design procedure for utilizing this method for the optimal design of fixture layouts in multi-station sheet metal assemblies.

4.7 Paper F: Optimal strategy of individualization

The methods and tools presented in the previous papers facilitate the evaluation of the results of implementing the different strategies followed in the individualization. Figure 4.11 presents an overview of these strategies. In general, six different strategies can be followed in the design of fixture layouts based on the applied input variations and the goal of the optimization in the design. If combining both techniques of selective assembly and individualized locator adjustments is not considered, based on the results of Paper D, two production strategies can also be followed in the production. The first production strategy is to utilize only selective assembly, and the second strategy is to utilize only individualized locator adjustments.

The primary source of the variation in assemblies is part variation. Nevertheless, when the goal is to improve geometrical quality by adjusting the locators, higher sensitivity to locator adjustments might result in greater controllability of variations by the adjustments. The reason is that when locators' deviations are considered as noise, the goal is to minimize sensitivity to them. Nevertheless, when they are control parameters, increasing the sensitivity of the output to them might result in more controlla-

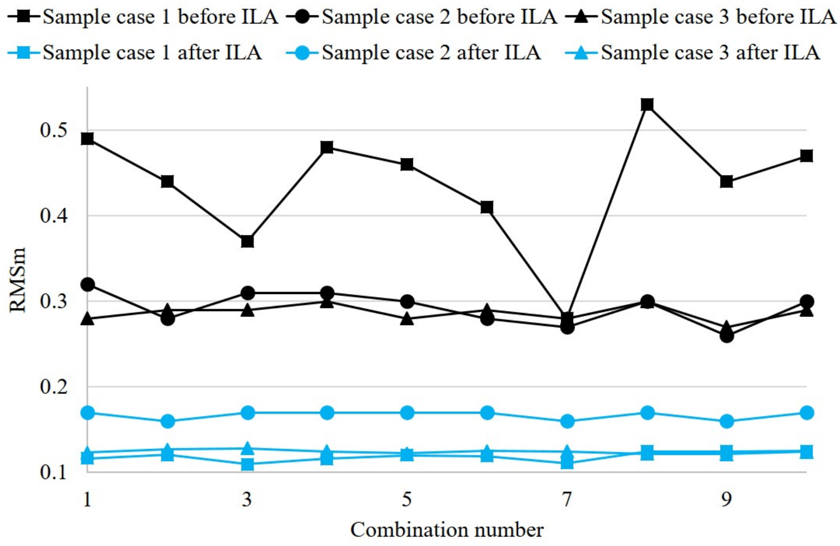


Figure 4.8: Fluctuation of RMS_v for different combinations of parts before and after applying individualized locator adjustments [Rezaei Aderiani et al., 2020c].

bility. For the same reason, having greater sensitivity to part deviations might result in more significant improvements through the selective assembly technique. Accordingly, six different design scenarios presented in Figure 4.11 are considered in this paper for evaluation.

The design and production strategies are evaluated by applying them to two sample cases. The geometrical quality of these sample cases is obtained when a design and production strategy is followed. Accordingly, for each sample case, 24 different scenarios are followed.

The results demonstrate that the first design strategy leads to the most significant improvements when production is conducted without use of a smart assembly line and when the selective assembly is employed. However, for a scenario in which the individualized locator adjustments technique is implemented, the third design strategy leads to the most remarkable improvements.

Among all possible scenarios, designing the fixture layout based on the third design strategy and utilizing individualized locator adjustments result in the most prominent geometrical quality. Thereafter, the scenario in which the first design scenario is utilized and selective assembly is employed results in the most remarkable improvements. The results of these scenarios are compared with production without individualization, and the first design strategy is presented in Table 4.3.

Table 4.3: Summary of achieved improvements by selective assembly (SA) and individualized locator adjustments (ILA) compared to assemblies without ILA/SA but with optimized fixture layout.

	SA [%]		ILA [%]	
	RMS_v	RMS_m	RMS_v	RMS_m
Sample case 1	5	1	30	40
Sample case 2	9	4	33	35

The results exhibit that use of an optimal fixture layout reduced the gap in the assemblies' geometrical quality produced with and without the selective assembly. However, the resulting improvements from individualized locator adjustments remain significant.

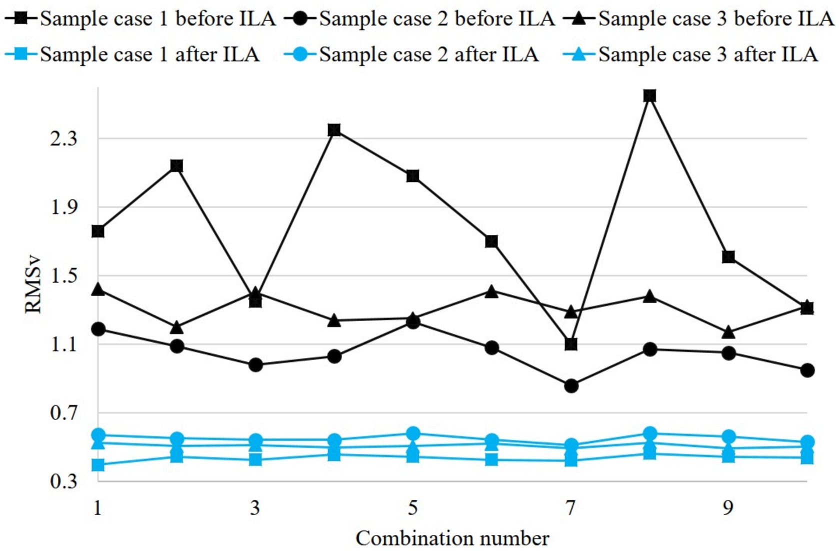


Figure 4.9: Fluctuation of RMS_m for different combinations of parts before and after applying individualized locator adjustments [Rezaei Aderiani et al., 2020c].

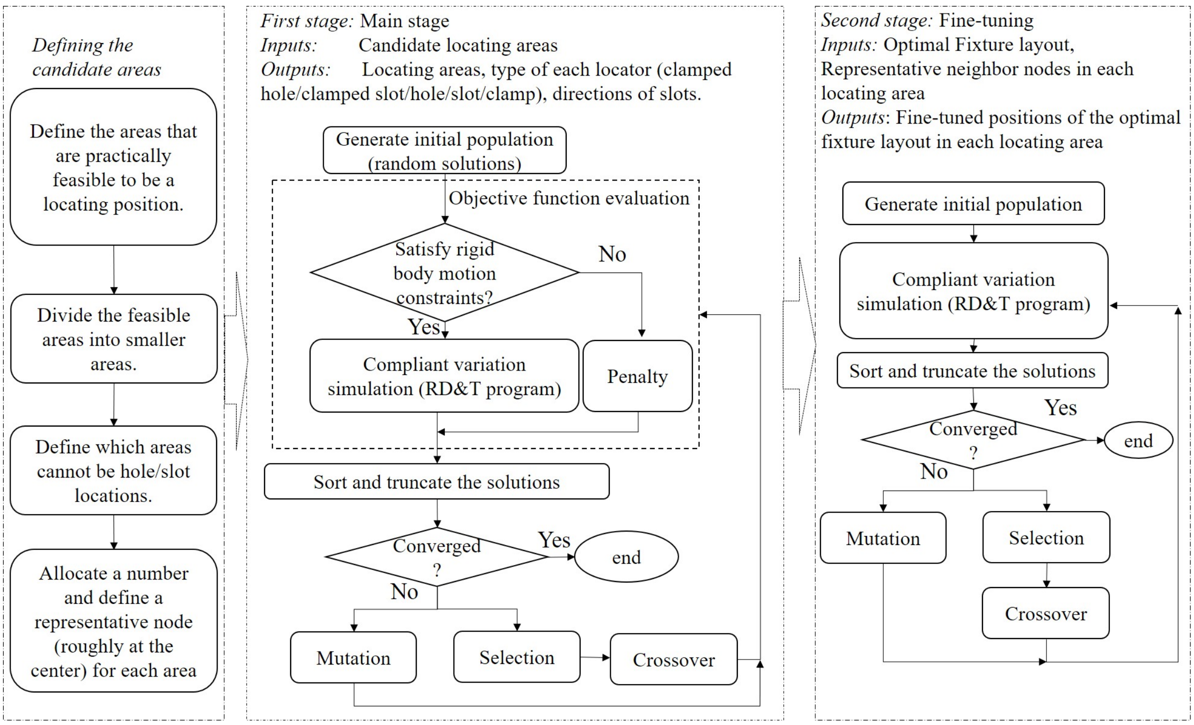


Figure 4.10: The overall design procedure design method presented in Paper E [Rezaei Aderiani et al., 2020a].

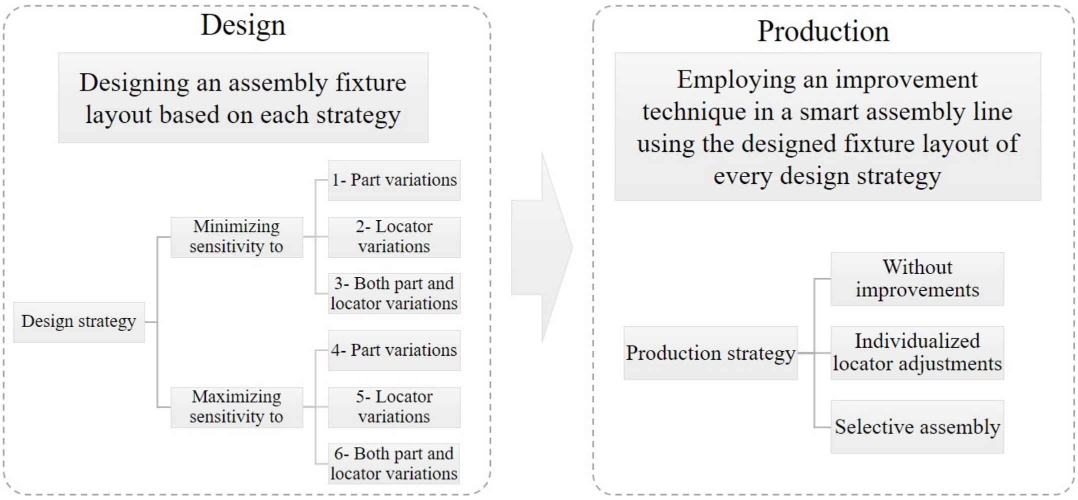


Figure 4.11: Different design and production strategies that can be followed for individualization [Rezaei Aderiani et al., 2020d].

CHAPTER 5

Discussion

This chapter discusses the results obtained and their relation to the research questions. Moreover, validation and verification of the results are discussed.

5.1 Answering the research questions

RQ 1: *How can selective assembly techniques be utilized in spot-welded sheet metal assemblies?*

Two of six papers in the thesis deal with answering the first research question. Paper A illustrates that the existing selective assembly methods do not apply to nonlinear assemblies, including sheet metals. This paper posits that it is not even clear whether the selective assembly technique can improve sheet metals' geometrical quality. The deviations of a high number of contact and welding points affect the deviations of the assembly, and matching all these deviations to obtain a better geometrical quality in assemblies may be impossible. Consequently, there is a hypothesis about the possibility of utilizing selective assembly of sheet metals that should also be addressed.

Paper A develops a selective assembly technique for sheet metals. Subsequently, evaluating the results of the method on three industrial sample cases, it evaluates the hypothesis regarding the possibility of improving quality using the selective assembly technique. The results demonstrate that the geometrical quality of sheet metals can improve using the selective assembly technique. The method presented in this paper is part of the response to how the geometrical quality of sheet metals can improve using selective assembly techniques.

Paper A indicates that changing batch sizes affects the improvements obtained from the selective assembly. Accordingly, it is required to clarify how the batch size influences geometrical quality to answer the first research question. This clarification is conducted by comparing the percentages of improvements in different batch sizes.

Paper A demonstrates that it is unreasonable for large problems to find the optimal combination of parts using deterministic algorithms, and meta-heuristics, including GAs, are preferred. Paper B unveils a problem in use of evolutionary algorithms to find the optimal combination of parts. This problem lies in the existing method of coding the phenotype to genotype, and Paper B copes with the problem by developing a new method for mapping. The presented method improves the convergence rate of optimization and is a step toward utilizing the selective assembly technique in a real-time control system.

In sum, the traditional selective assembly technique practiced in the industry, fixed-bin selective assembly , cannot be utilized for sheet metals. Selective assembly for sheet metals can be conducted in its individualized form. Variation simulation tools should be utilized along with meta-heuristic optimization methods to apply this technique.

RQ 2: *How can individualization in locator adjustments improve the geometrical quality of spot-welded sheet metal assemblies?*

To answer this question, a method of performing individualized adjustments for compliant assemblies is required. The literature review in Paper C indicates that the aforementioned method has not been previously developed. Hence, Paper C develops a method of performing individualized adjustments without limitations on rigidity. Paper C also clarifies that some stress limits should be considered in the adjustments applied and demonstrates this application in the method presented.

By applying both non-individualized and individualized adjustments to three sample cases, Paper C elucidates the advantages of individualization in improving the geometrical quality of assemblies. The results of this paper indicate that individualizing the locator adjustments can improve the geometrical quality of a batch of assemblies by 80% compared with no adjustments, up to three times more than non-individualized adjustments. It also evidences that performing the adjustment non-individualized may reduce the geometrical quality of some assemblies, whereas this problem does not exist in individualized adjustments.

Paper C also presents a modification in generating the initial population of the GA for individualized locator adjustments. This modification results in obtaining the same improvements with fewer adjustments. These improvements are vital, because they reduce the introduced stresses in the assemblies and adjustment work.

RQ 3: *What are the effects of combining selective assembly and individualized locator adjustments in a smart assembly line?*

Paper D addresses this question by evaluating three scenarios of production individualization. The results of this study suggest that combining the two techniques might not result in a remarkable difference from implementing only individualized locator adjustments. The reason is that the sensitivity of the assemblies reduces notably with the application of individualized locator adjustments. This reduction is sound because individualized locator adjustments address the same cause (part variation) as selective assembly addresses. Therefore, no matter whether this cause is mitigated by selective assembly, individualized locator adjustments considerably reduce it. Therefore, the reduction in the effect (assembly variations) is the same after individualized locator adjustment. A simple example of this phenomena for further clarification is to filter a light wave by two filters. Removing the filter with lower filtration power does not change the outcome of filtration.

RQ 4: *What are the effects of assembly fixture layout on the achievable geometrical improvements of selective assembly and individualized locator adjustments?*

The answer to this question is mainly illustrated in Paper F. However, the results presented in Paper F are obtained by utilizing the methods developed in Paper E. Paper E develops a new method of designing the fixture layouts for compliant sheet metal assemblies. This method is then utilized in Paper F to evaluate different strategies that can be followed to design fixture layouts based on the improvements achievable by individualization methods.

The results of employing different fixture layouts signify that the fixture layout is a vital factor in the achievable geometrical quality with and without individualization. The sensitivity of assemblies to locator adjustments and part combinations depends on the fixture layout for the assembly.

The fixture layout affects both the geometrical quality of the assembly and its sensitivity to the input factors, including locator adjustments and part combinations. Accordingly, what should be considered in the fixture layout design for individualized production is not only the sensitivity of assemblies to the input parameters. The criterion for defining the proper fixture layout should instead be the ultimate geometrical quality of the assemblies. A fixture layout may maximize improvements achievable through individualization but reduce the geometrical quality before individualization. In that case, the resulting geometrical quality might still be worse than when no individualization is applied.

The experiments conducted through simulations in Paper E designate that the design strategies that minimize the sensitivity of assemblies to the input parameters are superior to the strategies that maximize the sensitivity. The reason is that the strategies that maximize the sensitivity (the achievable improvements) reduce geometrical quality to the extent that it becomes worse than other strategies even after improvements. Another critical factor in designing fixture layouts that should be adjusted based on the individualization technique utilized for the production is the source of input variation. The most proper fixture layout for individualized locator adjustments is when variations are applied to both parts and locators. However, for production through the selective assembly, the input variations should be mainly part variations, as they are in practice. .

5.2 Limitations

Several factors could not be controlled based on the scope and availabilities of the research. These factors and their probable consequences should inform consideration of the results of this research.

The first limit is the number of available sample cases for the simulations. There were mainly three industrial sample cases available during this research. These sample cases are utilized for several experiments. Two sample cases are assemblies of two components each, and the other has three components. The results might not be the same for the assemblies with more components. However, it is not practical to investigate assemblies with all different numbers of components because there are no limits on the number of parts that an assembly can have. Moreover, these assemblies represent a majority of the assemblies in the automotive industry. The utilized sample cases have a relatively complex geometry (i.e., include 3D curves and are not developed in only one plane). Hence, a typical sheet metal assembly in a that which is a compliant assembly of two to four components joined by spot-welds has a 3D geometry, and curvatures in contact areas are covered by the utilized sample cases. Furthermore, having valid results for assemblies with at least two different numbers of parts indicates that changing the number of parts does not refute the conclusions.

Another limitation is the availability of real data of scanned parts of batches. For each sample case, the scan data of only one produced part was available. Therefore, the simulated deformed parts are generated by applying deformations to some areas of nominal models so that similar shapes are gained as the available scanned data for one part. Consequently, the generated deformations have similar magnitudes and patterns as do real deformed parts. However, the variation of these deformations in a batch might not be similar to that of a real batch of produced parts. The consequence of this limitation can be errors in the magnitude of improvements reported in this research. However, the methods and tools presented would remain valid. The descriptive results would also be valid, because the relation among different parameters may not change regardless of their values.

Drawing conclusions for physical assemblies through simulations has drawbacks. In the real world, noise and unseen factors might affect the results' outcome. Ambient temperature, dust, and adjustment errors are some of these factors. Nevertheless, most of these factors can be controlled depending on their effects and the required accuracy in the environment. In addition, this research aims to present the potential of individualization and pave the way for further investigations on this topic. It might not be reasonable to start with physical tests and experiments when it is possible to investigate the phenomenon through simulations at a considerably lower cost.

5.3 Research contribution

The contribution of research can be presented in two categories: industrial and scientific. Scientific contributions add knowledge where a research gap exists. Industrial contributions address a practical industrial problem. Nevertheless, there might not be a concrete barrier between these two types of contributions. A research gap can be an industrial problem, and the industry might practically apply the answer to a research question. Correspondingly, the contributions of this research might not divide cleanly along these categories because they can be practiced in industries while contributing to academic research.

Individualized assembly processes have been limited to a few categories of products. However, due to recent advances in technology, they can be developed for more complex products. This research presents the potential for the individualization of the assembly process in improving the geometrical quality of assemblies. Leveraging new technologies in different industries can be a game-changer in the future of production. The methods presented in this research can be utilized in different industries, particularly the automotive and aerospace industries, to improve their products' geometrical quality or to reduce production costs for the same geometrical quality.

The methods and tools developed in the appended papers help to fill the academic gaps and industrial practices in applications and studies of selective assembly, individualized adjustments, and fixture layouts design. The contributions can be summarized as follows:

- a selective assembly technique for sheet metal assemblies;
- an understanding of the effect of batch size on geometrical quality improvements in the selective assembly of sheet metals;
- improvement of the convergence rate of optimization in solving selective assembly problems using meta-heuristic algorithms by presenting a modification in the coding process;
- two methods of individualized and non-individualized locator adjustments;
- an understanding of the influence of individualization in locator adjustments;
- a modification in the optimization algorithm of individualized locator adjustments to reduce the required adjustments for the same improvements;
- a clarification of the outcome of different scenarios that can be practiced for individualization in a smart assembly line;
- a practical method for designing optimal fixture layouts for compliant sheet metal assemblies; and
- a set of optimal design and production strategies that can be followed to achieve the more outstanding geometrical improvements in assembly processes' individualization.

5.4 Research quality

The quality of research is commonly evaluated by its contribution to the subject of the study [Karlsson, 2016]. The contributions of this research yield prescriptive and descriptive results, as demonstrated in Figure 3.4.

The validity of these results is evaluated by investigating whether the right methods are utilized to perform the research. In other words, can the utilized methods be utilized to draw these conclusions? Can the research be considered scientific research? In verifying the results, the main concern is to check whether the utilized methods are carried out correctly. Accordingly, Sections 5.4.1 and 5.4.2 discuss the validation and verification of the research, respectively.

5.4.1 Validity of research

This research contributed by prescribing some new methods (Papers A, B, C, and E) and describing some relations among different design and production factors (Papers D and F). The validity of the prescribed methods is checked by applying them to several sample cases. The descriptive results are also presented based on experiments with several sample cases. Hence, the results are generalized for similar products, A method usually referred to as induction.

A well-known example of questioning the validity of induction is to consider a sheep that observes that its owner gives it food and takes care of it every day. The sheep can then infer from these observations that this procedure will happen forever (i.e., it is a "fact" that the owner will give it food and take care of it every day). However, one day the owner will come and take the sheep to slaughter it. How close are the conclusions of this research to the conclusion of the sheep?

This issue is not a problem raised by this research and has been a concern of philosophers from time of Aristotle. Even the most well accepted results and conclusions in science, including gravity and the Earth's rotation, can be questioned in the same way [Knowles, 2006].

There is no consensus among philosophers about how this concern can be addressed. Some of them, including Hume and Popper, argue that induction cannot be used for validation at all, and it can only be utilized in falsification [Hume et al., 2000]. Popper concludes that a hypothesis that is not falsifiable is unscientific. Moreover, a hypothesis is more falsifiable if it can be refuted by more observations' statements (observations such that if they occur, the hypothesis will be refuted). Therefore, although we cannot prove the validity of a hypothesis, using falsifiability, we can evaluate whether one hypothesis is truer than another, or as Popper says, whether it has more "verisimilitude" [Jarvie et al., 2006].

There are several objections to Popper's ideas about induction and falsifiability. One of these objections argues that if we reject induction, we cannot even falsify a hypothesis. If an observation refutes a hypothesis, the reason can be an error in the observation itself and not the hypothesis. The only method that can be utilized to make sure the observations are valid is induction. Therefore, if induction cannot be utilized for validation, there is no way to prove that the observations are valid, and the hypothesis is false.

Another approach presented by Kuhn for validating results is to see the history behind the hypothesis and its relation to other well-accepted hypotheses among experts in the field. He proposes the concept of a "paradigm" as the combination of related elements of the context among a community of scientists. Accordingly, the paradigms may not represent the truth, but they make progress through "paradigm shifts" [Kuhn, 1970].

Kuhn's ideas of paradigms have also been subjected to objection and criticism. Among those, Feyerabend notices that based on Kuhn's idea of paradigm, science is defined as more the opinions of some communities than of what represents reality [Feyerabend, 1993].

The definition of science and scientifically valid results is controversial to some extent. Among all philosophers and experts who have addressed this issue, Laudan's definition [Laudan, 1978], known as *normative naturalism*, seems closer to what the results of this research aim to present as science. Based on Laudan's ideas, a method is scientific if the validity of the results is measured empirically by their success in fulfilling the goals that they aimed to achieve. Accordingly, science may not aim to find the "truth" or even "truer" in the world, but to fulfill some defined aims. As expected, this view has also been criticized. For instance, criticism is how to define the goals and aims and whether they can be affected by previously accepted aims. Nevertheless, these concerns may not be directly relevant to this research, since the goals of this research are defined based on improvements in specific products.

Based on the ideas presented, this research can be considered scientifically valid if it can be empirically demonstrated that the results will fulfill the aims. Therefore, the question will not be whether the results present the truth of the world, but whether they will fulfill the goals of the research. In other words, are the generalizations conducted by induction valid?

The general method of this research is not purely inductive. The method utilized to obtain the prescriptive results can be categorized as hypothetical deductive methods [Knowles, 2006]. In papers A, B, C, and E, a design or production method or tool is developed mainly by deductive reasoning. For instance, in paper A, the method developed for the selective assembly of sheet metals is a combination of mathematical reasoning in the form of an optimization algorithm that is deductive. Hence, the function of this method is tested by applying it to several sample cases. If the results of applying the method on the sample cases do not present improvement, the method is false. Hence, the presented hypothesis is falsifiable.

Obtaining the expected results from sample cases does not prove that the method will lead to the expected results in all other sample cases. However, if more sample cases present improvement, the probability of the generality of the method improves. Even if the expected results were not obtained for the sample cases, it would not mean the method is false. In that case, the reason could be measurement errors (i.e., simulation errors). Nevertheless, that would lead to a lower probability of the hypothesis being valid.

The descriptive conclusions of the research that are mainly drawn in papers D and E are purely inductive. Accordingly, their validity is not 100% proven. However, the experiments are designed and carried out based on previous knowledge (i.e., what is generally accepted as science). Accordingly, there is a coherency between the results of this research and those of previously accepted results in the scientific communities. This coherence increases the validity of the results compared to general inductive reasoning not based on previously accepted knowledge.

Another measure of relative validity is acceptance by the community in which the research topic is subject of concern. This validity can be achieved by presenting the research at related conferences and well-known journals in the field. Another means of evaluating the validity of such research is to present and discuss it with the practitioners and engineers who work in the field of the research subject, for whom the problem presented by the research is a concern. Thanks to the close cooperation of the research group in which this research is conducted and engineers at Volvo Cars and GKN, the results and methods have been presented and discussed at different research stages.

The sample cases' selection has also been performed so that a broader range of sample cases are tested. Some factors can play an essential role in the achievable improvements. One of these factors include the number of parts of the assembly. Hence, this research has aimed to have sample cases with a different number of parts to evaluate effects of this factor on the results. In addition, the sample cases are provided from the automotive and aerospace industries, which are the most directly relevant industries for this research and are subject to the generalizations conducted. These factors add to the conclusions' validity and the probability that they will fulfill the intended goals.

5.4.2 Research verification

Verification of the results has been practiced over the entire research process with different techniques and methods. Some of these methods can verify that the entire process is performed in an acceptable quality. For instance, the acceptance of the results by researchers and experts in the field can verify the results to some extent, as it is also a sign of validity. This verification method is referred to as *comparison to other models* and *face validity* by Sargent et al. [Sargent, 2010].

Another approach to verify the entire process of obtaining the results is to evaluate whether they make sense based on previous knowledge and experience. For example, it makes sense that following the method presented in Paper E results in obtaining an optimal design of the fixture layouts based on mathematical logic.

Some verification methods can verify only a specific part of the entire work. These techniques are utilized particularly in the modeling and simulations performed. *Animation*, *parameter variability sensitivity analysis*, and *trace* [Sargent, 2010] are some of the methods utilized to verify the modeling and simulation of the assembly processes. For instance, the mesh size and the number of contact elements are verified by sensitivity analysis. The models are simulated by coarser and finer mesh size. If the variation of the results is smaller than the required accuracy, the mesh size is verified. The outcome of the methods and tools of variation simulations used in this study are verified by previous studies [Wärmefjord et al., 2010].

In order to simulate the variations that are close enough to real variations in assembly lines, some deformed parts should be imported to the simulation model. Since there were insufficient scanned data of parts to import them, the deformed parts are only generated randomly by MC simulations. The use of these parts as deformed parts is verified by generating the color-coding of their deformations and comparing them with scan data for physically produced parts. Moreover, checking the generated graphs of the deformed parts can reveal whether they are continuous and within the range of defined tolerances.

5.5 Future work

This research determines that individualization is promising in improving the geometrical quality of spot-welded sheet metal assemblies. The results were, however, based on simulations. The next step to advance this research is to conduct empirical experiments to further evaluate the presented techniques and tools.

The main focus of this research is mainly technical aspects of individualization. Other aspects, including the logistics, supply chain, and life cycle management of these products, should be evaluated in the future studies. Another subject of future work is to improve the computational efficiency of optimization for both selective assembly and individualized locator adjustments.

CHAPTER 6

Conclusions

In this research, ways of improving the geometrical quality of sheet metals by individualizing the assembly process are studied. The focus is on two techniques of selective assembly and individual adjustments of locators. The existing methods of performing these techniques are studied, gaps are found, and methods and tools are presented for support. It can be concluded from the results that both selective assembly and individualized adjustments of locators are promising techniques for improving the geometrical quality of assemblies. Accordingly, the individualization of the assembly process can considerably improve the geometrical quality of products.

The main conclusions drawn in the context of selective assembly are as follows:

- The improvement by the selective assembly for rigid and linear assemblies covers only dimensional variation, whereas for compliant sheet metals, both dimensional variation and mean deviation can improve.
- • Increasing the batch size in sheet metals leads to increase in the percentage of improvement in the mean deviation but reduces the percentage of improvement in variation.
- Utilizing the presented method of mapping from phenotype to genotype in Paper B improves the convergence rate of optimization.

The conclusions regarding the individualized adjustments of locators can be listed as follows:

- Performing individualized adjustments of assembly locators can increase improvements in the variation and mean deviation of all assemblies three to four times over non-individualized adjustments.
- Performing non-individualized adjustments of locators may reduce the geometrical quality of some assemblies, though the average quality of all assemblies improves. However, the individualized adjustments improve the geometrical quality of all assemblies.
- • Utilizing the modification presented in Paper C about the optimization algorithm results in reducing the required adjustments for the same improvements.

The conclusions regarding combining the two techniques can be listed as follows::

- Combining the selective assembly and individualized locator adjustment may not result in a significant improvement over employing only individualized locator adjustments.
- The sensitivity of assemblies to part combinations is remarkably diminished by applying individualized locator adjustments.

The conclusions about the effect of the fixture layout on individualization can be listed as follows:

- The assembly fixture layout of an assembly plays a primary role in determining achievable improvements by individualization.
- The optimal fixture layout for an assembly depends on the type of individualization technique employed.
- The optimal strategy to design a fixture layout for assemblies produced by a selective assembly technique is to consider part variations as the noise factor and minimize their sensitivity.
- The optimal strategy to design a fixture layout for assemblies produced by individualized locator adjustments is to consider locator deviations and part variations as the noise factor and thus to minimize their sensitivity.
- The improvements achievable by individualized locator adjustments are significantly greater than those of the selective assembly technique.

References

[Andersson, 2000] Andersson, J. (2000). A survey of multiobjective optimization in engineering design.

[Anwer et al., 2014] Anwer, N., Schleich, B., Mathieu, L., and Wartzack, S. (2014). From solid modelling to skin model shapes: Shifting paradigms in computer-aided tolerancing. *CIRP Annals*, 63(1):137–140.

[Asada and By, 1985] Asada, H. and By, A. (1985). Kinematic analysis of workpart fixturing for flexible assembly with automatically reconfigurable fixtures. *IEEE Journal on Robotics and Automation*, 1(2):86–94.

[Asha et al., 2008] Asha, A., Kannan, S., and Jayabalan, V. (2008). Optimization of clearance variation in selective assembly for components with multiple characteristics. *International Journal of Advanced Manufacturing Technology*, 38:1026–1044.

[Babu et al., 2018] Babu, M., Franciosa, P., and Ceglarek, D. (2018). Shape error modelling and analysis by conditional simulations of gaussian random fields for compliant non-ideal sheet metal parts. *Procedia CIRP*, 75:279 – 284. The 15th CIRP Conference on Computer Aided Tolerancing, CIRP CAT 2018, 11-13 June 2018, Milan, Italy.

[Bäck, 1996] Bäck, T. (1996). *Evolutionary Algorithms in Theory and Practice*. Oxford University Press.

[Bärring et al., 2020] Bärring, M., Johansson, B., and Stahre, J. (2020). Digital technologies enabling data of production systems for decision support. *Smart and Sustainable Manufacturing Systems*, 4(2).

[Bean, 1994] Bean, J. C. (1994). Genetic Algorithms and Random Keys for Sequencing and Optimization. *ORSA Journal on Computing*, 6(2):154–160.

[Beasley et al., 1993] Beasley, D., Bull, D., and Martin, R. (1993). An overview of genetic algorithms: Pt1, fundamentals. *University Computing archive*, 15:58–69.

[Beckmann et al., 2015] Beckmann, A., Litwa, F., and Bohn, M. (2015). Meta Modelling of body-in-white processes as a sustainable knowledge base during series production. In *NAFEMS world Congress 2015*, San Diego.

[Bergström et al., 2018] Bergström, P., Fergusson, M., and Sjödahl, M. (2018). Virtual projective shape matching in targetless cad-based close-range photogrammetry for efficient estimation of specific deviations. *Optical Engineering*, 57:57 – 68.

[Blessing and Chakrabarti, 2009] Blessing, L. T. and Chakrabarti, A. (2009). *DRM, a design research methodology*. Springer.

[Blum and Roli, 2003] Blum, C. and Roli, A. (2003). Metaheuristics in combinatorial optimization: Overview and conceptual comparison. *ACM Comput. Surv.*, 35(3):268–308.

[Bokrantz et al., 2020] Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T., and Stahre, J. (2020). Smart maintenance: a research agenda for industrial maintenance management. *International Journal of Production Economics*, 224:107547.

[Brinkhuis and Tikhomirov, 2005] Brinkhuis, J. and Tikhomirov, V. (2005). *Optimization: Insights and Applications: Insights and Applications*. Princeton University Press.

[Burgess, 1984] Burgess, R. (1984). *In the Field*. Routledge.

[Cai, 2008] Cai, W. (2008). A new tolerance modeling and analysis methodology through a two-step linearization with applications in automotive body assembly. *Journal of Manufacturing Systems*, 27(1):26–35.

[Cai et al., 1996] Cai, W., Hu, S. J., and Yuan, J. X. (1996). Deformable Sheet Metal Fixturing: Principles, Algorithms, and Simulations. *Journal of Manufacturing Science and Engineering*, 118(3):318.

[Cai et al., 2006] Cai, W. W., Hsieh, C.-C., Long, Y., Marin, S. P., and Oh, K. P. (2006). Digital panel assembly methodologies and applications for compliant sheet components. *Journal of manufacturing science and engineering*, 128(1):270–279.

[Chan and Linn, 1999] Chan, K. and Linn, R. (1999). A grouping method for selective assembly of parts of dissimilar distributions. *Journal of Quality Engineering*, 11(2):221–234.

[Chase and Parkinson, 1991] Chase, K. W. and Parkinson, A. R. (1991). A survey of research in the application of tolerance analysis to the design of mechanical assemblies. *Research in Engineering design*, 3(1):23–37.

[Checkland, 1989] Checkland, P. B. (1989). Soft systems methodology. *Human systems management*, 8(4):273–289.

[Dahlström and Lindkvist, 2007] Dahlström, S. and Lindkvist, L. (2007). Variation simulation of sheet metal assemblies using the method of influence coefficients with contact modeling. *Journal of manufacturing science and engineering*, 129(3):615–622.

[Dantzig, 1961] Dantzig, G. (1961). *Maximization of a linear function of variables subject to linear inequalities*. Wiley and Chapman-Hall.

[Deb et al., 2002] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2):182–197.

[Duffy and Andreasen, 1995] Duffy, A. and Andreasen, M. (1995). Enhancing the evolution of design science. In *Proceedings of ICED*, volume 95, pages 29–35.

[Duffy and O'Donnell, 1999] Duffy, A. H. and O'Donnell, F. (1999). *A design research approach*. Norges teknisk-naturvitenskapelige universitet.

[Eshelman and Schaffer, 1993] Eshelman, L. J. and Schaffer, J. D. (1993). Real-coded genetic algorithms and interval-schemata. In *Foundations of genetic algorithms*, volume 2, pages 187–202. Elsevier.

[Evans, 1975a] Evans, D. H. (1975a). Statistical tolerancing: The state of the art. *Journal of Quality Technology*, 7(1):1–12.

[Evans, 1975b] Evans, D. H. (1975b). Statistical tolerancing: The state of the art - methods for estimating moments. *Journal of Quality Technology*, 7:1–12.

[Fang and Zhang, 1995] Fang, X. and Zhang, Y. (1995). A new algorithm for minimizing the surplus parts in selective assembly. *Computer and Industrial Engineering*, 28(2):341–350.

[Feyerabend, 1993] Feyerabend, P. (1993). *Against Method*. Verso.

[Forslund et al., 2018] Forslund, A., Lorin, S., Lindkvist, L., Wärmefjord, K., and Söderberg, R. (2018). Minimizing Weld Variation Effects Using Permutation Genetic Algorithms and Virtual Locator Trimming. *Journal of Computing and Information Science in Engineering*, 18(4):041010.

[Franciosa et al., 2011] Franciosa, P., Gerbino, S., and Patalano, S. (2011). Simulation of variational compliant assemblies with shape errors based on morphing mesh approach. *The International Journal of Advanced Manufacturing Technology*, 53(1):47–61.

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

[Germer et al., 2014] Germer, C., Nagat, M., and Klenk, T. (2014). Die virtuelle Messdatenanalyse bei Volkswagen. *Konstruktion*, 66(10):94–98.

[Goldberg, 1991] Goldberg, D. (1991). Real-coded genetic algorithms, virtual alphabets, and blocking. *Complex Syst.*, 5.

[Goldberg and Deb, 1991] Goldberg, D. E. and Deb, K. (1991). A comparative analysis of selection schemes used in genetic algorithms. In *Foundations of genetic algorithms*, volume 1, pages 69–93. Elsevier.

[Holland et al., 1992] Holland, J. H. et al. (1992). *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence*. MIT press.

[Hong and Chang, 2002] Hong, Y. and Chang, T. (2002). A comprehensive review of tolerancing research. *International Journal of Production Research*, 40(11):2425–2459.

[Hume et al., 2000] Hume, D., Beauchamp, T., Beauchamp, P., and Press, O. U. (2000). *An Enquiry Concerning Human Understanding: A Critical Edition*. Clarendon Hume Edition Series. Clarendon Press.

[Jarvie et al., 2006] Jarvie, I., Milford, K., and Miller, D. (2006). *Karl Popper: A Centenary Assessment Volume I*. Karl Popper: A Centenary Assessment. Ashgate Pub. Limited.

[Ju et al., 2017] Ju, F., Li, J., and Deng, W. (2017). Selective assembly system with unreliable bernoulli machines and finite buffers. *IEEE Transactions on Automation Science and Engineering*, 14(1):171–184.

[Kannan et al., 2005] Kannan, S., Asha, A., and Jayabalan, V. (2005). A new method in selective assembly to minimize clearance variation for a radial assembly using genetic algorithm. *Journal of Quality Engineering*, 17(4):595—-607.

[Kannan et al., 2009] Kannan, S., Sivasubramanian, R., and Jayabalan, V. (2009). A new method in selective assembly for components with skewed distributions. *International Journal of Productivity and Quality Management*, 4:569–589.

[Karlsson, 2016] Karlsson, C. (2016). *Research methods for operations management*. Routledge.

[Keller, 2014] Keller, C. (2014). Force-controlled adjustment of car body fixtures. *Procedia CIRP*, 23(C):89–97.

[Keller and Putz, 2016] Keller, C. and Putz, M. (2016). Force-controlled Adjustment of Car Body Fixtures - Verification and Performance of the New Approach. *Procedia CIRP*, 44:359–364.

[Knowles, 2006] Knowles, J. (2006). *Theory of Science: A Short Introduction*. Tapir Akademisk Forlag.

[Kritzinger et al., 2018] Kritzinger, W., Karner, M., Traar, G., Henjes, J., and Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 51(11):1016 – 1022. 16th IFAC Symposium on Information Control Problems in Manufacturing INCOM 2018.

[Kuhn, 1970] Kuhn, T. S. (1970). *The structure of scientific revolutions, second edition, enlarged*. University of Chicago Press.

[Kumar et al., 2007] Kumar, M., Kannan, S., and Jayabalan, V. (2007). A new algorithm for minimizing surplus parts in selective assembly by using genetic algorithm. *International Journal of Production Research*, 45(20):4793–4822.

[Kumar et al., 2009] Kumar, M., Sivasubramanian, R., and Jayabalan, V. (2009). Particle swarm optimization for minimizing assembly variation in selective assembly. *International Journal of Advanced Manufacturing Technology*, 42:793—803.

[Lanza et al., 2015] Lanza, G., Haefner, B., and Kraemer, A. (2015). Optimization of selective assembly and adaptive manufacturing by means of cyber-physical system based matching. *CIRP Annals - Manufacturing Technology*, 64(1):399–402.

[Laudan, 1978] Laudan, L. (1978). *Progress and Its Problems: Towards a Theory of Scientific Growth*. Campus (Berkeley). University of California Press.

[Lindau et al., 2013] Lindau, B., Lindkvist, L., Andersson, A., and Söderberg, R. (2013). Statistical shape modeling in virtual assembly using pca-technique. *Journal of Manufacturing Systems*, 32(3):456–463.

[Lindau et al., 2016] Lindau, B., Lorin, S., Lindkvist, L., and Söderberg, R. (2016). Efficient contact modeling in nonrigid variation simulation. *Journal of Computing and Information Science in Engineering*, 16(1).

[Lindkvist et al., 2005] Lindkvist, L., Carlson, J. S., and Söderberg, R. (2005). Virtual Locator Trimming in Pre-Production: Rigid and Non-Rigid Analysis. *ASME 2005 International Mechanical Engineering Congress and Exposition*, pages 561–568.

[Lindkvist and Söderberg, 2003] Lindkvist, L. and Söderberg, R. (2003). Computer-aided tolerance chain and stability analysis. *Journal of Engineering Design*, 14(1):17–39.

[Liu and Hu, 1997] Liu, S. and Hu, S. (1997). Variation simulation for deformable sheet metal assemblies using finite element methods. *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, 119(3).

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

[Lorin et al., 2012] Lorin, S., Lindkvist, L., Söderberg, R., and Sandboge, R. (2012). Combining variation simulation with thermal expansion for geometry assurance. *17th Design for Manufacturing and the Life Cycle Conference*, 5:477–485.

[Lu et al., 2020] Lu, Y., Liu, C., Wang, K. I.-K., Huang, H., and Xu, X. (2020). Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing*, 61:101837.

[Lupuleac et al., 2011] Lupuleac, S., Petukhova, M., Shinder, Y., and Bretagnol, B. (2011). Methodology for solving contact problem during riveting process. *SAE International Journal of Aerospace*, 4(2011-01-2582):952–957.

[Madrid, 2018] Madrid, J. (2018). *Design for Manufacturing and Producibility in Fabricated Aerospace Structures*. PhD thesis, Chalmers University of Technology.

[Mansor, 1961] Mansor, E. (1961). Selective assembly-its analysis and applications. *International Journal of Production Research*, 1(1):13–24.

[Menassa and DeVries, 1989] Menassa, R. J. and DeVries, W. R. (1989). Locating Point Synthesis in Fixture Design. *CIRP Annals*, 38(1):165–169.

[Nair et al., 1992] Nair, V. N., Abraham, B., MacKay, J., Box, G., Kacker, R. N., Lorenzen, T. J., Lucas, J. M., Myers, R. H., Vining, G. G., Nelder, J. A., et al. (1992). Taguchi's parameter design: a panel discussion. *Technometrics*, 34(2):127–161.

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

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

[Pinzone et al., 2020] Pinzone, M., Albè, F., Orlandelli, D., Barletta, I., Berlin, C., Johansson, B., and Taisch, M. (2020). A framework for operative and social sustainability functionalities in human-centric cyber-physical production systems. *Computers and Industrial Engineering*, 139:105132.

[Polini and Corrado, 2020] Polini, W. and Corrado, A. (2020). Digital twin of composite assembly manufacturing process. *International Journal of Production Research*, 0(0):1–15.

[Ponnambalam et al., 2006] Ponnambalam, S., Sankar, S. S., Sriram, S., and Gurumarimuthu, M. (2006). Parallel populations genetic algorithm for minimizing assembly variation in selective assembly. *Proc. International Conference on Automation Science and Engineering, Shanghai, China.*

[Pugh, 1992] Pugh, G. A. (1992). Selective assembly with components of dissimilar variance. *Computer and Industrial Engineering*, 23(1–4):487—491.

[Rezaei Aderiani et al., 2018] Rezaei Aderiani, A., Wärmefjord, K., and Söderberg, R. (2018). A Multistage Approach to the Selective Assembly of Components without Dimensional Distribution Assumptions. *Journal of Manufacturing Science and Engineering*, 140(7):071015.

[Rezaei Aderiani et al., 2019a] Rezaei Aderiani, A., Wärmefjord, K., and Söderberg, R. (2019a). Developing a Selective Assembly Technique for Sheet Metal Assemblies. *International Journal of Production Research*, 57(22):7174–7188.

[Rezaei Aderiani et al., 2020a] Rezaei Aderiani, A., Wärmefjord, K., Söderberg, R., Lindkvist, L., and Lindau, B. (2020a). Optimal design of fixture layouts for compliant sheet metal assemblies. *The International Journal of Advanced Manufacturing Technology*, 110:2181–2201.

[Rezaei Aderiani et al., 2020b] Rezaei Aderiani, A., Wärmefjord, K., and Söderberg, R. (2020b). An Improved Phenotype-Genotype Mapping for Solving Selective Assembly Problem Using Evolutionary Optimization Algorithms. *Journal of Computing and Information Science in Engineering*, 20(6). 061010.

[Rezaei Aderiani et al., 2020c] Rezaei Aderiani, A., Wärmefjord, K., and Söderberg, R. (2020c). Combining selective assembly and individualized locator adjustments in a smart assembly line. *CIRP CATS*, pages 1–15.

[Rezaei Aderiani et al., 2020d] Rezaei Aderiani, A., Wärmefjord, K., and Söderberg, R. (2020d). Evaluating different strategies to achieve the highest geometric quality in self-adjusting smart assembly lines. *Robotics and Computer-Integrated Manufacturing*, pages 1–15.

[Rezaei Aderiani et al., 2019b] Rezaei Aderiani, A., Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2019b). Individualizing Locator Adjustments of Assembly Fixtures Using a Digital Twin. *Journal of Computing and Information Science in Engineering*, 19(4):041019–041028.

[Sadeghi Tabar et al., 2019] Sadeghi Tabar, R., Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2019). A Novel Rule-Based Method for Individualized Spot Welding Sequence Optimization With Respect to Geometrical Quality. *Journal of Manufacturing Science and Engineering*, 141(11).

[Sargent, 2010] Sargent, R. G. (2010). Verification and validation of simulation models. In *Proceedings of the 2010 Winter Simulation Conference*, pages 166–183. IEEE.

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

[Schleich et al., 2019] Schleich, B., Dittrich, M.-A., Clausmeyer, T., Damgrave, R., Erkoyuncu, J. A., Haefner, B., de Lange, J., Plakhotnik, D., Scheidel, W., and Wuest, T. (2019). Shifting value stream patterns along the product lifecycle with digital twins. *Procedia CIRP*, 86:3 – 11. 7th CIRP Global Web Conference – Towards shifted production value stream patterns through inference of data, models, and technology (CIRPe 2019).

[Schmitt et al., 2017] Schmitt, R., Corves, B., Loosen, P., Brecher, C., Jeschke, S., Kimmelmann, W., Hüsing, M., Stollenwerk, J., Bertelsmeier, F., Detert, T., et al. (2017). Cognition-enhanced, self-optimizing assembly systems. In *Integrative Production Technology*, pages 877–990. Springer.

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

[Siiskonen et al., 2020] Siiskonen, M., Malmqvist, J., and Folestad, S. (2020). Integrated product and manufacturing system platforms supporting the design of personalized medicines. *Journal of Manufacturing Systems*, 56:281 – 295.

[Siiskonen, 2019] Siiskonen, M. D. I. (2019). *Integrated Product and Production Platforms for Pharmaceutical Products: Design Thinking for the Development of Personalized Medicines*. PhD thesis, Chalmers Tekniska Hogskola (Sweden).

[Söderberg, 1993] Söderberg, R. (1993). Tolerance allocation considering customer and manufacturing objectives. *Advances in Design Automation*, 2:149–157.

[Söderberg, 1994a] Söderberg, R. (1994a). Robust design by tolerance allocation considering quality and manufacturing cost. *Advances in Design Automation*, 69:1.

[Söderberg, 1994b] Söderberg, R. (1994b). Tolerance allocation in a CAD environment considering quality and manufacturing cost. *Lean Production: From Concept to Product*, pages 789–800.

[Söderberg and Lindkvist, 1999] Söderberg, R. and Lindkvist, L. (1999). Computer aided assembly robustness evaluation. *Journal of Engineering Design*, 10(2):165–181.

[Söderberg et al., 2006] Söderberg, R., Lindkvist, L., and Carlson, J. (2006). Virtual geometry assurance for effective product realization. In *Proceedings of 1^{ST} Nordic Conference on Product Lifecycle Management - NordPLM0́6*, Gothenburg Sweden.

[Söderberg et al., 2006] Söderberg, R., Lindkvist, L., and Carlson, J. (2006). Virtual geometry assurance for effective product realization. In *First Nordic Conference on product Lifecycle Management-NordPLM'06*, Göteborg, Sweden.

[Söderberg et al., 2006] Söderberg, R., Lindkvist, L., and Dahlström, S. (2006). Computer-aided robustness analysis for compliant assemblies. *Journal of Engineering Design*, 17(5):411 – 428.

[Söderberg et al., 2017] Söderberg, R., Wärmefjord, K., Carlson, J. S., and Lindkvist, L. (2017). Toward a digital twin for real-time geometry assurance in individualized production. *In CIRP Annals*, 66:137—140.

[Taguchi et al., 1989] Taguchi, G., Elsayed, E. A., and Hsiang, T. C. (1989). *Quality engineering in production systems*. McGraw-Hill College.

[Tan and Wu, 2012] Tan, M. H. and Wu, C. F. J. (2012). Generalized selective assembly. *IIE Transactions*, 44(1):27–42.

[Tao et al., 2018] Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., and Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, 94(9):3563–3576.

[Thornton, 2004] Thornton, A. C. (2004). *Variation risk management: focusing quality improvements in product development and production*. John Wiley & Sons.

[Velásquez and Nof, 2009] Velásquez, J. and Nof, S. (2009). Best-matching protocols for assembly in e-work networks. *International Journal of Production Economics*, 122(1):508 – 516. Transport Logistics and Physical Distribution Interlocking of Information Systems for International Supply and Demand Chains Management ICPR19.

[Wärmefjord et al., 2008] Wärmefjord, K., Lindkvist, L., and Söderberg, R. (2008). Tolerance simulation of compliant sheet metal assemblies using automatic node-based contact detection. In *ASME 2008 International Mechanical Engineering Congress and Exposition*, pages 35–44. American Society of Mechanical Engineers.

[Wärmefjord et al., 2016] Wärmefjord, K., Söderberg, R., Lindau, B., Lindkvist, L., and Lorin, S. (2016). Joining in nonrigid variation simulation. *Computer-aided Technologies–Applications in Engineering and Medicine*.

[Wärmefjord et al., 2010] Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2010). Variation simulation of spot welding sequence for sheet metal assemblies. In *Proceedings of NordDesign*.

[WMF, 2018] WMF (2018). *World Manufacturing Forum Report, Recommendations for The Future of Manufacturing*. World Manufacturing Forum.

[Wright and Davidson, 2020] Wright, L. and Davidson, S. (2020). How to tell the difference between a model and a digital twin. *Advanced Modeling and Simulation in Engineering Sciences*, 7(13).

[Wärmefjord et al., 2010] Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2010). Strategies for Optimization of Spot Welding Sequence With Respect to Geometrical Variation in Sheet Metal Assemblies. In *ASME International Mechanical Engineering Congress and Exposition*, volume Volume 3: Design and Manufacturing, Parts A and B, pages 569–577.

[Wärmefjord et al., 2020] Wärmefjord, K., Söderberg, R., Schleich, B., and Wang, H. (2020). Digital twin for variation management: A general framework and identification of industrial challenges related to the implementation. *Applied Sciences*, 10(10).

[Wu and Tang, 1998] Wu, C. and Tang, G. (1998). Tolerance design for products with asymmetric quality losses. *International Journal of Production Research*, 36(9):2529–2541.

[Xing and Wang, 2018] Xing, Y. and Wang, Y. (2018). Minimizing assembly variation in selective assembly for auto-body parts based on igaot. *International Journal of Intelligent Computing and Cybernetics*, 11(2):254–268.

Paper A

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., (2019), 'Developing a selective assembly technique for sheet metal assemblies", International Journal of Production Research, 57(22): 7174-7188.

Paper B

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2019), “An Improved Phenotype-Genotype Mapping for Solving Selective Assembly of Sheet Metals Using Evolutionary Optimization Algorithms ”, ASME Journal of Computing and Information Science in Engineering, 20(6): 061010-061018.

Paper C

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., (2019), ‘Individualizing Locator Adjustments of Assembly Fixtures Using a Digital Twin”, Journal of Computing and Information Science in Engineering, 19(4): 041019-041028.

Paper D

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2020), “Combining Selective Assembly and Individualized Locator Adjustments Techniques in a Smart Assembly Line”, Procedia CIRP, 97:429-434.

Paper E

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., Lindau, B., (2020), “Optimal Design of Fixture Layouts for Compliant Sheet Metal Assemblies”, International Journal of Advanced Manufacturing Technology, 110: 2181–2201.

Paper F

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2021), "Evaluating Different Strategies to Achieve the Highest Geometric Quality in Self-adjusting Smart Assembly Lines", Journal of Robotics and Computer-Integrated Manufacturing.