THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

IMPROVING GEOMETRICAL QUALITY BY INDIVIDUALIZING THE ASSEMBLY PROCESS

ABOLFAZL REZAEI ADERIANI

CHALMERS

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABOLFAZL REZAEI ADERIANI

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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 increases production costs. Availability of larger amounts of data and automatized production has opened new opportunities to improve the geometrical quality of products by individualization of the assembly process. This concept is proposed by Söderberg et al. as Smart Assembly 4.0 in which the individualized matching of parts, locator adjustments, weld sequence optimization, etc. are performed on an assembly line.

This study focuses on two techniques of individualizing the assembly process, individualized matching of parts and individualized locator adjustments in assembly fixtures. The existing studies and applications of these methods are reviewed and gaps defined. The previous applications of individual matching of parts, known as selective assembly, are limited to linear and rigid assemblies. This study improves existing methods by presenting a multistage method of performing selective assembly technique without dimensional assumptions about the mating parts. This method results in improved geometrical quality compared to similar methods and no surplus parts. This study also develops the application of selective assembly for sheet metal assemblies. The assembly technique developed for sheet metals is applied to three industrial sample cases to evaluate its performance. Another gap in the context of selective assembly covered by this study is a problem in the existing method of mapping in the utilized optimization algorithm.

This research also studies individualized adjustments of locators in assembly fixtures. After evaluating the existing methods of locator adjustments, this study develops a new method that utilizes the scanned data 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. Thereafter, both methods are applied to three industrial sample cases and the results evaluated. A modification is also proposed that reduces the required adjustments for the same amount of improvements in geometrical quality.

The results of this research evidence a promising improvement in the geometrical quality of assemblies by individual matching of parts and locator adjustments. The results illustrate that individualization in locator adjustments can increase geometrical quality improvements three to four times.

Keywords: Selective Assembly, Locator Adjustments, Individual assembly processes, Geometry Assurance, Variation Simulations.

Acknowledgments

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Abolfazl Rezaei Aderiani
Gothenburg, Sweden, April 9, 2019

Publications

The following publications are included in this thesis:

Paper A

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2018), ”A Multistage Approach to the Selective Assembly of Components Without Dimensional Distribution Assumptions”, *Journal of Manufacturing Science and Engineering*, 140(7): 071015-071015-8.

Paper B

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., Lindkvist, L., (2019), ‘Developing a selective assembly technique for sheet metal assemblies”, *International Journal of Production Research*, https://doi.org/10.1080/00207543.2019.1581387

Paper C

Rezaei Aderiani, A., Wärmefjord, K.; Söderberg, R., (2019), “An Improved Phenotype-Genotype Mapping for Solving Selective Assembly of Sheet Metals Using Evolutionary Optimization Algorithms ”, *IEEE Journal of Robotics and Automation Letters*, Submitted

Paper D

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*, Accepted.

Contents

CHAPTER 1

Introduction

The deviation of geometry from its nominal position is inevitable in the production of parts, although this deviation may be within an allowable tolerance, because every production tool has a limited precision and accuracy in production. Consequently, geometrical variations appear in the mass production of parts. These variations may cause both functional and aesthetical problems in the final product. In addition, they impose a combined quality cost, including scraps, repairs, reworks, etc. Accordingly, 10 to 40 percent of the revenue in the automotive industry is being lost because of these variations [Thornton, 2004]. Figure 1.1 presents a list of combined quality costs.

There are different methods to cope with the problem of geometrical variations, including six sigma, Taguchi methods, Statistical Process Control, etc. [Söderberg, 1994]. However, the main difference among these methods is the cost of applying each method and the amount of improvement that can be achieved. Some of these methods, including Six Sigma, Taguchi method, SPC and variation risk management, require experimental tests on the produced parts [Taguchi et al., 2005].

Nowadays, subjects such as Big Data, cyber factories, and production automation are getting more attention and it is predicted that in the future more data will be available further in production lines [Söderberg et al., 2017, Colledani et al., 2014]. For example, deviations of all produced parts from their nominal state can be obtained using an online shape inspection method by taking some pictures from each part and quickly analyzing those pictures [Bergström et al., 2018]. Therefore, utilizing this opening in minimizing the effects of variation, geometry assurance can be a game changer in the competitive world of production and product development.

In the next section, an overview will be given of the context of geometry assurance. Thereafter, the research gap in this field will be clarified. Afterward, the questions that this research is trying to answer based on the gap are reviewed. The

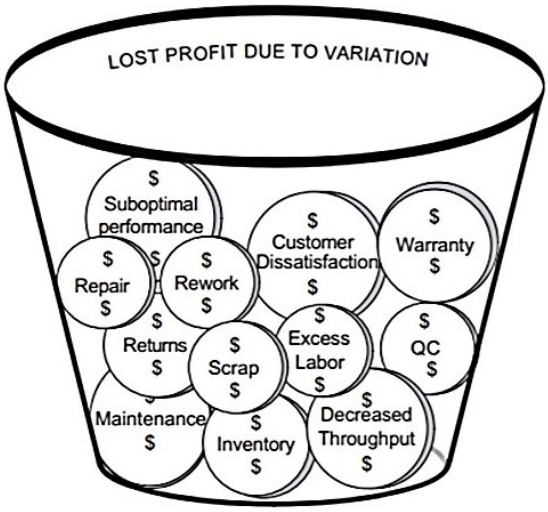

Figure 1.1: The problems raised due to geometrical variation [Thornton, 2004].

final section outlines the structure of this thesis.

1.1 Geometry assurance

Geometry assurance is a set of activities aim at reducing of the effect of variation in aesthetical and functional attributes of the products [Söderberg et al., 2006]. These activities can be conducted in different phases of product development, including concept design, verification and production phases; see Figure 1.2.

There are different causes for generating variation in produced parts depending on the production process. Regardless of the cause, it is usually expensive and difficult to reduce the variation in part production. Geometry assurance activities try to minimize the effect of existing variations, in addition to reducing their sources. In the concept phase, a key objective is to set design parameters so that the product is not sensitive to part variations. Locating scheme of assembly fixtures and split lines of parts are two examples of these design parameters. In the verification phase, the adjustment of locators and shimming can be predicted by variation simulation tools. Geometry assurance activities in the production phase use inspection data in controlling production processes with the goal of minimizing the effects of variation.

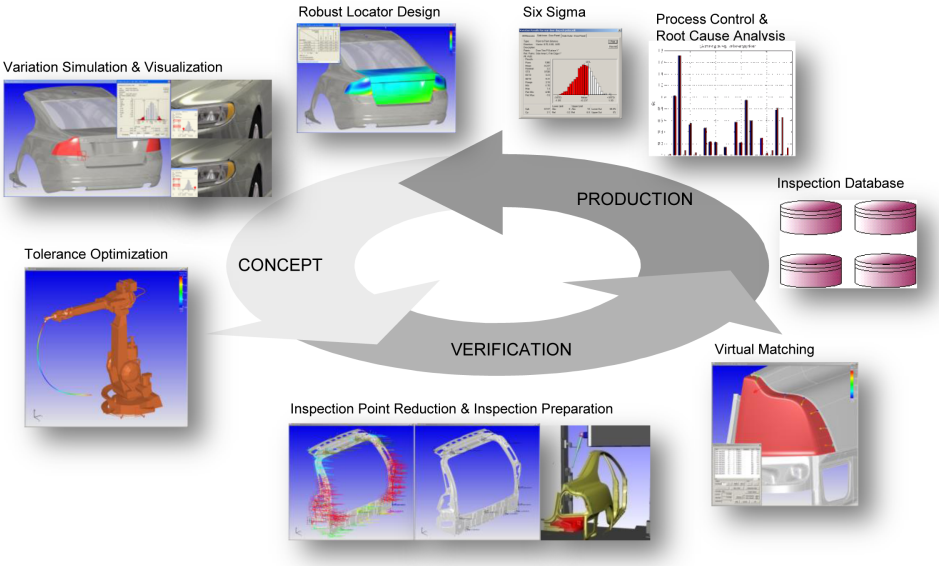

Figure 1.2: The geometry assurance framework in three main phases of product realization [Söderberg et al., 2006].

1.2 Smart Assembly 4.0

Taking advantage of the advances in production automation and available data of produced parts, Söderberg et al. proposed implementing a digital twin on an assembly line to obtain optimal production parameters and apply them to physical assemblies [Söderberg et al., 2017]. This concept is named Smart Assembly 4.0. Figure 1.3 illustrates a schematic image of this process.

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 be capable of predicting the geometrical deviations of the physical assembly. Therefore, the digital twin should be a computer-aided tolerancing (CAT) model to be used in variation simulations. The production parameters to be minimized include locators adjustments, weld sequence [Wärmefjord et al., 2016], and individual parts.

1.3 Research focus and goals

The primary focus of this research is studying individualized assembly processes, particularly matching mating parts and locator adjustments, in the concept of

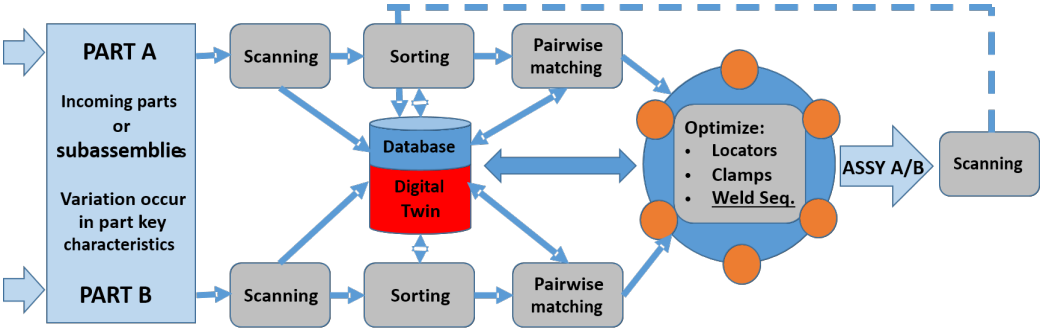

Figure 1.3: The proposed concept of Smart Assembly 4.0 by Söderberg et al. [Söderberg et al., 2017]

Smart Assembly 4.0. It means to assess 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 hypothesis is that applying these techniques to an assembly line has the potential of improving the geometrical quality of the products. The results of this research may help to evaluate this hypothesis.

Matching the mating 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 in improving the geometrical quality of assemblies. This goal is evolved by proceeding research. For instance, the results of Paper B illustrate that time is also a critical parameter that requires further improvements. Thereafter, reducing the elapsed time of calculations became the goal for Paper C. The existing selective assembly techniques are limited to linear and rigid assemblies. Consequently, this technique has not been studied previously for sheet metal assemblies. Moreover, there are some problems, such as surplus parts, even in the existing methods for rigid and linear assemblies.

Previous research and applications of locator adjustment in fixtures are limited to performing this technique on a batch of assemblies. Moreover, the scanned data of mating parts have not been utilized in predicting the adjustments. Therefore, the main goal in this context is to discover the potential for individualizing this technique based on the scanned data of mating parts in improving quality.

1.4 Research questions

Considering that the focus and primary goals of the research are in the twin contexts of individualized matching of parts and individualized locator adjustments, two research questions are formed as follows.

Research question 1: How can geometrical quality be improved by Individual Matching of parts?

This research question covers the problems and challenges involved in the individual matching of parts. This includes the existing method and tools, limits and challenges to their application and the required developments to solving them.

Research question 2: How can geometrical quality be improved by Individualized adjustments of locators of assembly fixtures?

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

1.5 Delimitation

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

The research questions can be answered from different aspects, including logistics, economy, and sustainability. Nevertheless, the focus of this thesis is on the technical aspects of this question, particularly geometry assurance. Therefore, the main gaps from these aspects are addressed in the appended papers. However, presenting the potential of individualization in this research can be a motivation for other researchers to study it from other aspects.

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 are dominant in the automotive and aerospace industries. Moreover, the mechan-

ical properties of mating parts 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 method presented 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 background of the research, the problems that the research is trying to solve, goals and questions that are attempted to be answered. The second chapter presents the frame of reference. This chapter reviews the main topics with which this research is dealing with. The third chapter discusses the methodology employed for conducting this research. The results of the appended papers and their connection to each other are presented in the fourth chapter. Thereafter, the fifth chapter discusses how these results answer the research questions and the main conclusions of the research are summarized in the sixth chapter.

Acronyms

MLS	Master Locating System
CAT	Computer Aided Tolerancing
MIC	Method of Influence Coefficients
FEM	Finite Element Method
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
MINLP	Mixed Integer Non-linear Programing

CHAPTER 2

Frame of Reference

Several fields are touched by this research. Therefore, an overview of each field will be given in this chapter. The main focus of the research is studying individualized assembly processes to improve geometrical quality of the assemblies. Hence, different criteria for the assessment of geometrical quality are defined in the first section. The second section provides a brief background of Geometry Assurance, especially tolerance analysis and variation simulations. Two techniques in the assembly process on which this research focuses for individualization are selective assembly and adjustments of locating schemes. Accordingly, section three and four of this chapter review these techniques. The final section gives an overview of optimization since this research has utilized different optimization techniques in presenting new methods and tools.

2.1 Geometrical quality

The main focus of this research is on improving the geometrical quality of assembled products. Therefore, in this section, an overview of different definitions of geometrical quality and what is utilized in this research is given. The ideal geometry of a product is the geometry that intended by the designer, usually referred to as the nominal geometry. However, due to limits of production, the accuracy and precision with which this geometry can be achieved are limited. Consequently, there will be some deviations from the nominal dimensions in the manufactured products. These deviations can cause functional and aesthetical problems in the final product and it is desired to minimize them. Accordingly, different criteria for assessing geometrical quality are functions of these deviations. For instance, some areas or points in a product can be defined by the designer to limit their deviations from their nominal positions.

The criterion of geometrical quality for a single part or an assembly can be

defined as the deviation of a single point, several areas or the entire geometry of the product. When the goal is to assess the deviation of the entire product the Root Mean Square (RMS) of deviations of all points is considered. Equation 2.1 presents the definition of this parameter.

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

In this equation, d_i represents the deviation of the ith node and n is number of all nodes in the assembly. RMS_d is a proper criterion for geometrical quality assessment when the goal is to improve geometrical quality by changing some design or production parameters. This is because changing some parameters may improve the geometrical quality of an area and worsen it in other areas. Hence, if only certain points are considered for evaluating quality, the changes may result in reducing the quality in other points.

In mass production of parts and assemblies, there are other criteria with which to evaluate the geometrical quality of the entire batch of assemblies. These criteria are variation and mean deviations of specific dimensions. The former represents the precision and the latter presents the accuracy of dimensions. The difference between these two parameters is illustrated in Figure 2.1. The charts presented in this figure visualize the distribution of deviation for a dimension where the nominal mean value is zero. Hence, the accuracy is higher for distributions whose mean value is closer to zero. Nevertheless, the produced parts can have a high accuracy without being precise. This means that although the mean value of the dimension is close to zero, the individual dimensions have relatively high deviations.

In order to improve the geometrical quality of a batch, both variation and mean deviation should be improved.

The mean deviation of a point is defined as the average deviation of that point from its nominal position among all assemblies. Equation 2.2 presents this parameter for point i.

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

N in this equation represents the batch size.

Variation is statistically estimated using $6s$, defined as deviation of a point from its nominal position among all products. Equation 2.3 presents this definition.

$$6s_i = 6\sqrt{\frac{1}{N-1}\sum_{j=1}^{N}(d_{ij}-\bar{d}_i)^2} \tag{2.3}$$

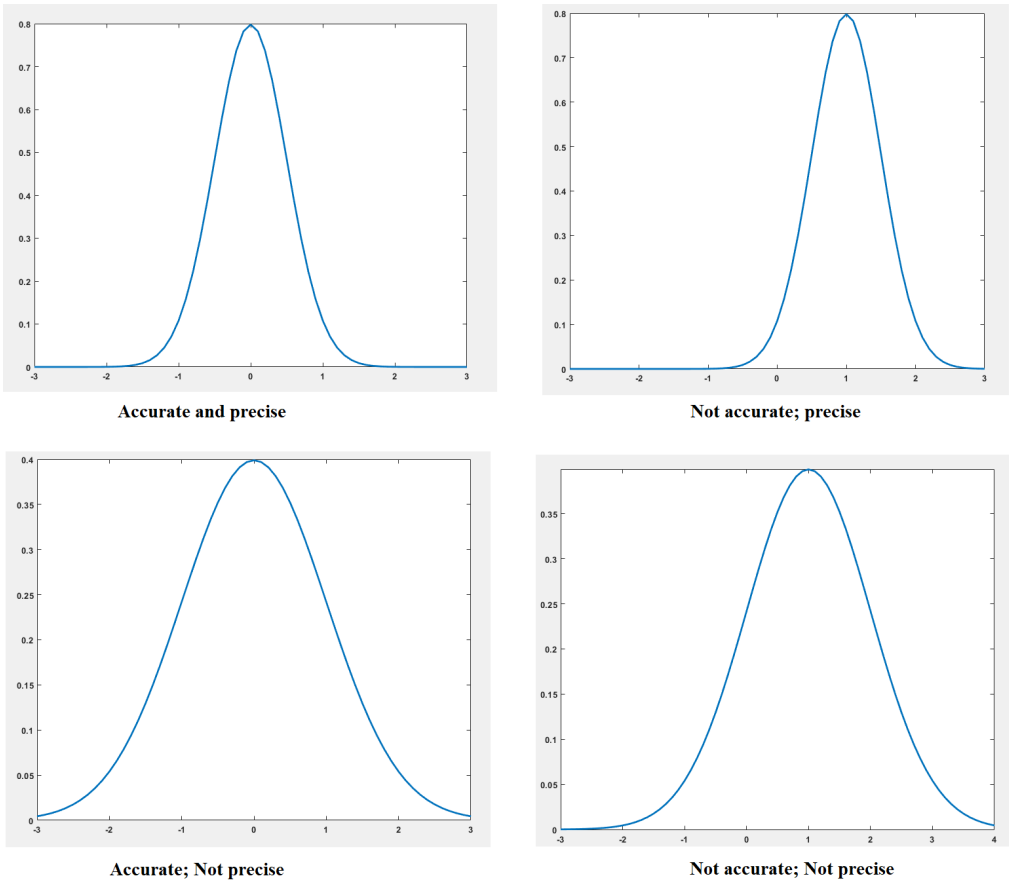

Figure 2.1: Difference between accuracy and precision.

In order to consider the geometrical quality of all areas of the product in a batch, RMS of variation, RMS_v, and mean deviation, RMS_m of all points can be considered. In other words, the variation and mean deviation of each point are obtained, then the RMS of these parameters are calculated among all points. Equations 2.4 and 2.5 present definitions of these parameters, respectively.

$$RMS_v = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(6s_i)^2} \tag{2.4}$$

$$RMS_m = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\bar{d}_i)^2} \tag{2.5}$$

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

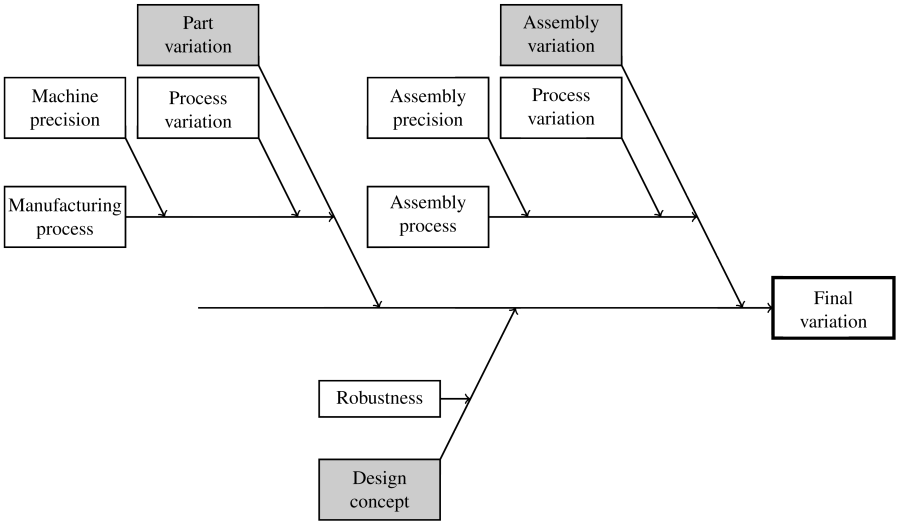

Figure 2.2: Contributors to final geometric variation [Söderberg et al., 2006].

2.2 Geometry assurance

There are a variety of activities that aim to cope with the problem of variation and are referred to as geometry assurance activities. As shown in Figure 1.2, geometry assurance can be performed from the concept design phase to full production. Nevertheless, in order to cope with the problem of variation, it is important to know the causes and sources thereof.

Geometrical variation of a final product primarily depends on the geometrical variation of its mating parts. The variation in mating parts comes from the accuracy and precision of production tools and variation in manufacturing processes. The variation of assembly processes will contribute to this variation and results in the final variation of the product. The variation of assembly processes can be the result of assembly fixtures, welding tools, etc. Söderberg et al. [Söderberg et al., 2006] have visualized the contribution of the different sources of variation in Figure 2.2.

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 conducted using two different approaches.

The first approach is known as top down tolerancing. In this approach, the tolerances of the final product will initially be defined. Thereafter, they will be broken down into sub-assemblies and parts [Söderberg, 1993, Söderberg, 1994, 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 the tolerances 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 important to be able 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 et al., 2007, Chase and Parkinson, 1991, Gao et al., 1998, Hong and Chang, 2002, Nigam and Turner, 1995, Hong and Chang, 2002]. The tolerance analysis can be performed in two general approaches; an analytical approach and the Monte Carlo (MC) approach.

In the analytical approach, the tolerances in the final product are predicted by utilizing the first order or the second order Taylor expansions of the function of input variations to output variations. The formulation of this expansion for the first order is presented in Equation 2.6. In this equation, X_i represents the input variations and μ indicates the mean value thereof.

$$f(X_1, X_2, \ldots, X_n) \approx f(\mu_1, \mu_2, \ldots, \mu_n) + \sum_{i=1}^{n} \frac{\partial f(\mu_1, \mu_2, \ldots, \mu_n)}{\partial x_i} (X_i - \mu_i), \qquad (2.6)$$

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 at the same time, the method is 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.

The Root Sum Square (RSS) method is one method where the root sum square of the sensitivity coefficients of the Taylor expansion is considered for predicting output variations. Equation 2.7 presents the formulation of this relation [Evans, 1975]. In this equation, T represents the output variation and t_is indicate the input variations. A main assumption of this method is that all input dimensions follow a normal distribution.

$$T = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f(\mu_1, \mu_2, \ldots, \mu_n)}{\partial x_i} t_i \right)^2} \tag{2.7}$$

In contrast to the worst case method, the RSS method is considered to be 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 to be more realistic method in analytical tolerance analysis [Chase and Parkinson, 1991, Wu and Tang, 1998, Lööf, 2010].

The second approach of tolerance analysis is MC-Simulation. In 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 for that specific input. Therefore, the distribution of the outputs can be predicted by analyzing the samples generated. Using this method, both linear and non-linear relations can be simulated.

The advantage of analytical methods of tolerance analysis is their low cost of computation. However, implementation of these methods can be complicated and their accuracy has also been questioned [Cai et al., 2006]. The MC-Simulation method, one the other hand, has a high calculation cost whereas its implementation is simpler and can be used for a larger variety of functions.

2.2.2 Variation simulations

Variation of a product can be predicted using variation simulations. Different sources of variation can be added to these simulations, including part variations and fixture variations. The input variations for the simulation can be scanned data of produced parts (in production phase) or they can be generated using the Monte Carlo method. Variation simulations can also be used to predict the variations of assemblies by simulating the assembly procedure when different sources of variation are considered.

In order to assemble parts, they should be fixed in their positions by some locators. For compliant parts, particularly sheet metals, they are fixed using some assembly fixtures. For instance, to assemble two sheet metal parts by welding, the parts are first fixed in the assembly fixture. Thereafter, they will be welded. Then, the assembly will be released from the fixture and induced stresses during the assembly procedure will cause spring back. Figure 2.3 illustrates this process.

The spring-back and geometry of the assembly after they have been released from fixtures depend on several parameters, including the initial deformed shape and stiffness of the mating parts, weld properties, locating scheme, etc.

The assembly process can be simulated by utilizing Finite Element Methods (FEM). There are several Computer Aided Tolerancing (CAT) tools for this pur-

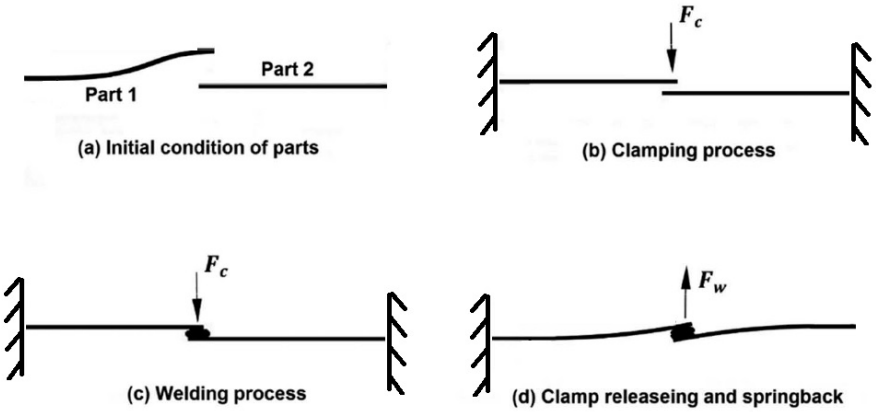

Figure 2.3: Four main steps in simulation of an assembly process.

pose including RD&T [RD&T, 2018] and 3DCS [3DCS, 2018]. The calculation cost of simulations can be reduced by implementing the Method of Influence Coefficient (MIC) [Liu and Hu, 1998]. In addition, combining this technique with contact modeling increases the accuracy of simulations [Wärmefjord et al., 2008].

The RD&T program has the capability of performing both rigid and compliant simulations. Contact modeling can also be utilized in this program. 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 deformations do not exceed the linear elastic range, fixtures and welding tools are not flexible, deformations due to temperature are negligible, materials are isotropic and the stiffness matrix remains constant for deformed part shapes. The detailed procedure of the variation simulation method that is utilized in RD&T is illustrated by [Söderberg and Lindkvist, 1999] and [Lindkvist and Söderberg, 2003].

2.3 Selective assembly

Matching mating parts in mass production of assemblies is known as the Selective Assembly Technique in the literature. Utilizing this technique can improve the geometrical quality of assemblies by selecting individual parts based on their

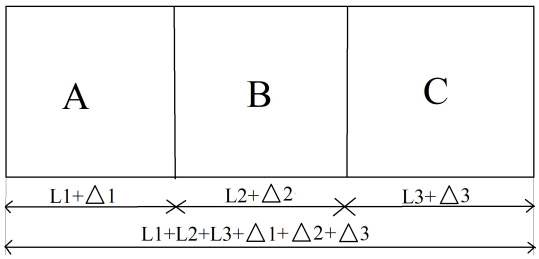

Figure 2.4: A sample linear assembly of three components.

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 2.4 (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, 1000 parts from each component should be produced. The nominal dimensions of components A, B and C are L1, L2, and L3, respectively. Nevertheless, the dimensions produced may have a variation compared to 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 in such a way that assembling their mating parts will result in the minimal variation in the target dimension of the assembly. 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.

Selective assembly technique has been utilized from the 1950's in engine and bearing industries [Mansor, 1961]. However, there has been a problem regarding this technique known as the mismatching problem. After dividing the parts into several groups and matching these groups, the number of parts in the matched groups may not be equal. Consequently, some parts in larger groups will be superfluous. Most of the early studies about selective assembly are concerned with this problem and present different methods to solving 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 these attempts [Chan and Linn, 1999].

Selective assembly is an optimization problem. Therefore, some studies have utilized optimization algorithms, especially evolutionary optimization algorithms, including Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), to solve this problem. These studies are mostly concerned with having minimal or zero surplus parts and minimizing the variation of the target dimension in the assemblies [Kannan et al., 2005, Kumar et al., 2009, Kannan et al., 2009].

Selective assembly technique has been limited to rigid and linear assemblies, where the target dimensions have a linear relation to some dimensions of the mating parts.

2.4 Locating schemes

A rigid part has six degrees of freedom in space, including three translations and three rotations. In order to position a part in a fixture, or other mating parts in an assembly, a locating scheme should be defined. The locating scheme describes the points and degrees of freedoms that each point locks. There are several types of locating schemes. One common locating scheme is 3-2-1. It means that three degrees of freedom are locked in a plane, two are locked in a line and one degree is locked in a point. This locating scheme is illustrated in Figure 2.5.

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 means the number of locators that are applied perpendicular to the sheet surface is more than three. The reason for having additional locators is usually to withstand external forces, including gravity.

It is possible to lock several degrees of freedom by utilizing holes and slots. This type of positioning is presented in Figure 2.6 as an example. A hole locks two directions and a slot locks a single direction.

An important factor that should be considered for designing a locating scheme is minimizing the sensitivity of the geometry to the variation in locating points. In a locating scheme with high sensitivity, a small variation can cause a larger variation in other areas of the geometry. Nevertheless, in a design that is not sensitive, the locators are placed in areas that the consequences of variation in them are minimal.

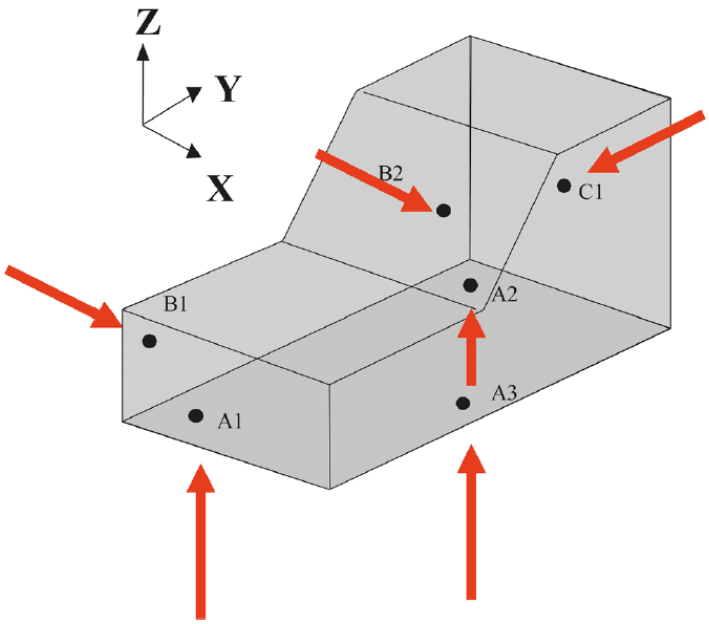

Figure 2.5: A 3-2-1 locating scheme.

2.5 Locator adjustments

Adjusting the locators is a technique in the assembly process in which the geometrical quality of products can be improved by performing minor adjustments to locators in their steering direction. This technique is also known as Shimming and Trimming. In shimming, some thin slots are manually added to the locating point of the fixture. There are some standard shims with different thicknesses that are traditionally selected based on previous experience or trial and error. Another means of adjusting is utilizing adjustable locators in the fixture instead of adding and removing the shims.

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 the adjustments [Germer et al., 2014,Beckmann et al., 2015]. In these methods, the input

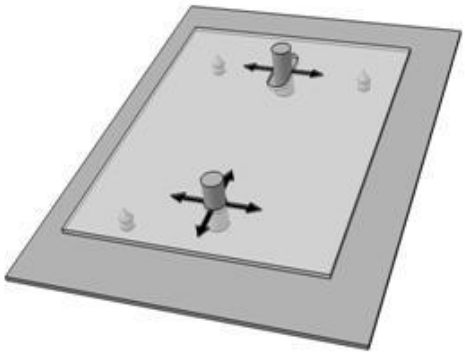

Figure 2.6: Implementation of a hole and a slot in a locating scheme [Wagersten, 2013].

data of the training phase are the amount of different adjustments 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 mating parts have not been utilized for determining these adjustments. Forslund et al. [Forslund et al., 2018] have utilized locator adjustments for rigid bodies to improve geometrical quality and strength of the rear structure of a jet engine. The adjustment in this study is conducted individually for each blade of the structure considering the blades are rigid.

2.6 Optimization

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 2.8 represents the mathematical formulation of this problem.

$$min f(\mathbf{x}) \tag{2.8}$$

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 be without any constraints or may have several constraints.

There are different criteria with which to categorize optimization problems and algorithms. Depending on the objective functions and constraints, the problem can be linear or nonlinear. If one or several parameters were limited to integer values, the problem belongs to the category of Integer Programming. Combinatorial optimization is another type of optimization problem where the goal is to find a set of objects from finite sets of objects that minimize the objective function. The Traveling Salesman Problem (TSP) is an example of combinatorial problems.

Optimization algorithms can be divided into the twin categories of metaheuristics and non-metaheuristics. Metaheuristic algorithms are usually independent of the optimization problem, whereas in non-metaheuristic algorithms the type of problem, particularly the objective function and constraints, is important. In other words, each non-metaheuristic algorithm can solve a specific type of problem. On the other hand, a disadvantage of metaheuristics is that they do not guarantee finding the optimal solution to the problem. Nevertheless, if the problem becomes too complicated to be solved by non-metaheuristics, metaheuristics can find solutions that are sufficiently good in a practical time with lower complicity [Blum and Roli, 2003]. Combinatorial optimizations, especially for relatively large size problems, are an example of these problems [Blum and Roli, 2003].

If there is more than a single objective function 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 to each other is known or if there is no priority among them. Nevertheless, it is sometimes 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 2.7 presents a Pareto Front for a two-objective optimization problem. In this figure, all solutions in the Pareto Front are superior to other solutions in at least one objective.

There are different methods for obtaining Pareto Front in multi-objective optimization. A comprehensive review of these methods is available in [Andersson, 2000].

2.6.1 Genetic algorithm

Genetic Algorithm 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 known as the pioneers of introducing GAs. The optimization procedure in this algorithm is illustrated in

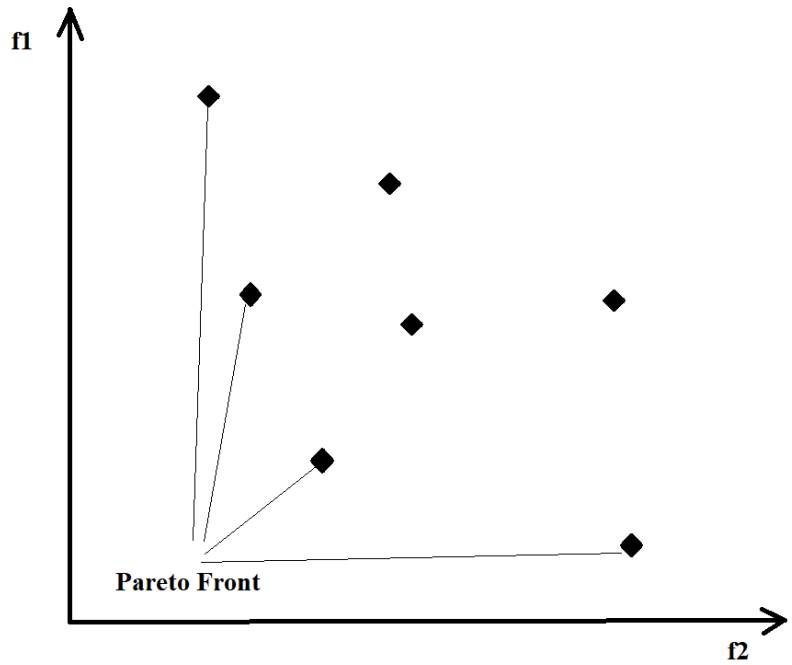

Figure 2.7: Pareto Front in a two-objective optimization problem.

Figure 2.8.

As shown in Figure 2.8, the first step is to generate some random solutions to the problem. These solutions are referred to as chromosomes. After calculating the objective of each solution using an objective function, a 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 higher probability to solutions with higher fitness. Thereafter, new solutions will be generated using genetic operators, including Crossover and Mutation. Therefore, solutions with the highest fitness among previous and new solutions create the next generation. Accordingly, solutions with lower fitness will be removed. This evolution 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 generations.

Crossover

In the crossover, two solutions that are selected will generate two new solutions. Depending on the type of problem, different types of crossover may be applied. The solutions that are selected for this operation are referred to as parents and

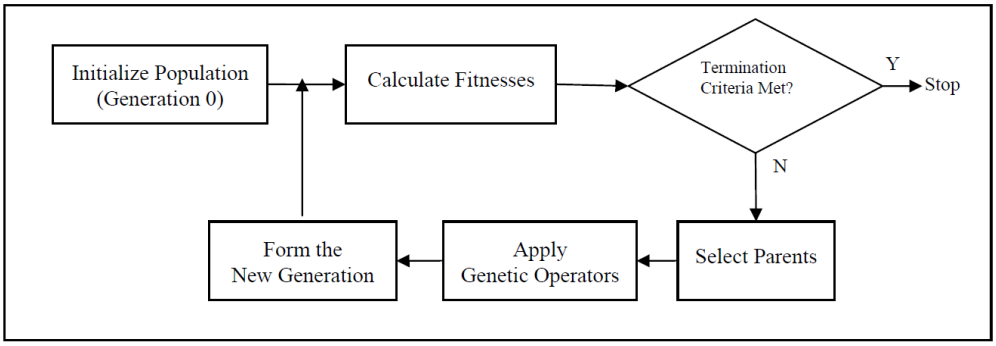

Figure 2.8: Genetic algorithm schematic.

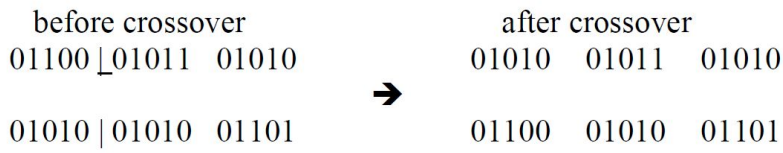

Figure 2.9: An example of a single-point crossover in a binary GA.

the solutions generated through this operation are known as children. Figure 2.9 presents a crossover between two binary parents. Since, the parents are divided at only one point, this crossover is a single-point crossover.

Mutation

Mutation is another genetic operator that applies small random changes to previous solutions. The goal in the operation is to avoid convergence of the algorithm in local optima. Mutation can be performed in different ways depending on the type of problem. For example, if the solutions are binary, mutation is usually performed by changing a random digit from 0 to 1 or vice-versa.

CHAPTER 3

Research Approach

This chapter briefly presents the background and elements of the research methodology utilized in this research.

3.1 Research methodology

3.1.1 Background

The research presented in the thesis relates to the context of design of the production process and, in particular, the assembly process. 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 is related to developing production strategies that respond to the need for improving geometrical quality. Therefore, Design Research Methodology (DRM) is utilized for performing this research. This research methodology is proposed by Blessing [Blessing and Chakrabarti, 2009] as a framework that includes four different stages to guarantee quality of research in the context of design. These four stages are described in the following list.

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

- Descriptive Study I: In this phase of the research, the literature review is

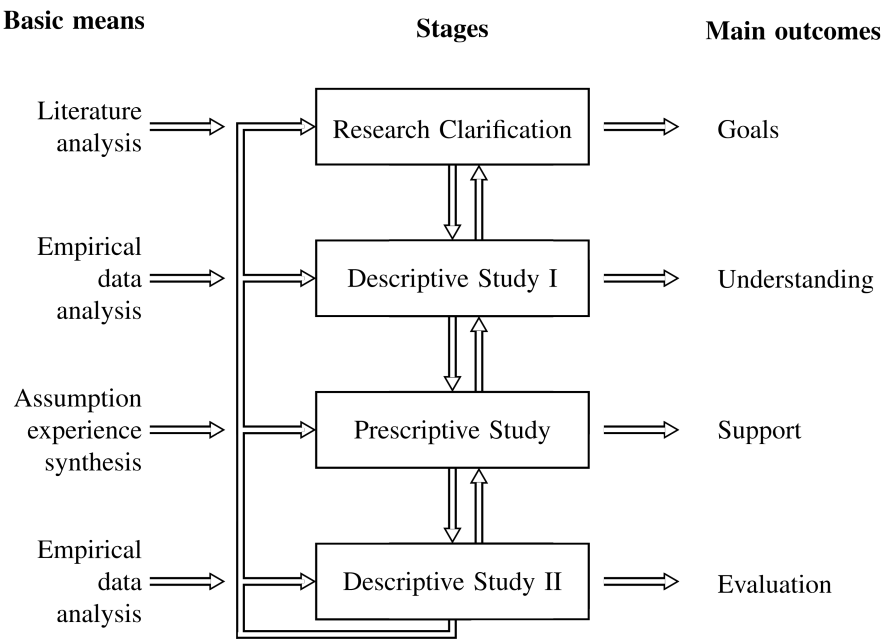

Figure 3.1: Design Research Methodology (DRM) by Blessing and Chakrabarti [Blessing and Chakrabarti, 2009].

usually detailed to realize the current situation and improve the initial understanding of the previous phase. In addition, the factors that may improve this situation will be clarified. Empirical studies may be performed if a knowledge gap should arise.

- Prescriptive Study: The goal of this phase is to develop some tools and methods to improve the current situation so that it approaches the desired situation.

- Descriptive Study II: This phase of the research is aiming to evaluate the improvements presented in the previous phase by measure of success criteria. As a result, it will be clarified if the intended improvements are achievable by the presented methods or tools.

A research study neither needs to include all four phases nor 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 of using these phases in design research.

3.1.2 Elements of the design research methodology in this research

This research aims at improving the geometrical quality by individualizing the assembly processes. Therefore, the first assumption is that individualization can improve the geometrical quality of assemblies. This assumption is made based on previous knowledge and literature analysis. During the first phase, Research Clarification, the preliminary success criteria for measuring the success of the presented methods to improve product quality are presented. These measurable success criteria vary for different assemblies based on the type of product, including rigidity and flexibility or if a batch of assemblies or a single assembly is considered to be the product. Accordingly, different success criteria for assessing geometrical quality are defined based on these factors, during this phase. For single assemblies, the measurable success criterion is considered to reducing RMS of deviations of all points from their nominal positions. On the other hand, the criteria for a batch of assemblies are defined as reducing the RMS of variation and mean deviations of all points among all assemblies. These criteria are illustrated in Papers B and D, respectively.

The assumption based on previous knowledge and initial literature analysis is that the techniques that can be utilized in individualization to improve geometrical quality are matching mating parts, adjustments of fixture locators and optimization of the weld sequence. The focus of this research is defined in the first two techniques and therefore, RQ1 and RQ2 are defined based thereof.

Performing literature analysis in Descriptive Phase I discovers the existing gaps in utilizing the techniques mentioned. These studies and gaps are addressed in Papers A, B and D. The first gap in Paper A highlights that the existing method of matching parts, which is known as the Selective Assembly technique, does not result in the optimal reduction of dimensional variation of assemblies. The second gap, which is covered in Paper B, is that the selective assembly technique is only studied for rigid and linear assemblies and not for the sheet metal assemblies that are dominant in the automotive and aerospace industries. The third gap is the lack of studies of individualized adjustments of locator fixtures that were defined in the first phase by RQ2.

In the prescriptive phase of the study, new methods and tools are presented to cover the gaps defined and improve the success of the products, here defined as the geometrical quality of assemblies.

The methods and tools presented in the first prescriptive study are verified in the second descriptive study by applying them to three industrial cases. The results of this application and the results of the second descriptive study discover another success criterion for the selective assembly of sheet metals. This success criterion is the time for obtaining the optimal combination of mating parts. Considering

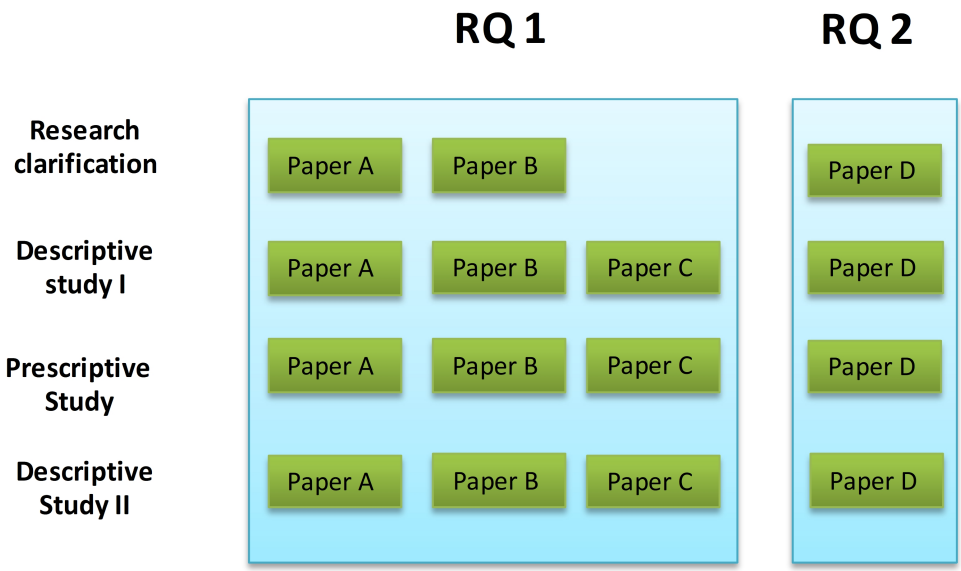

Figure 3.2: The distribution of Paper A-D in the context of DRM.

this, another iteration is conducted in Research Clarification by adding a success criterion to previous criteria. Afterward, detailed literature studies are performed about reducing this time. Thereafter, the second iteration of the prescriptive study is performed by presenting a method by which this success criterion for selective assembly technique is improved, in addition to the second iteration of Descriptive study II by evaluating this method against industrial cases. Paper C of the thesis covers the second iterations of all stages based on the success criterion of time discovered and the existing gap in that context. Figure 3.2 lists the distribution of papers on different phases and research questions.

3.2 Utilized methods

Different methods are utilized in each phase of the research to attain the goals of that phase, presented in this section.

3.2.1 Literature studies

To analyze the current situation and existing methods by which the quality by individualization can be improved, literature studies is the most important method that has been utilized. Accordingly, in all papers, literature analysis is performed

in order to understand the current situation, clarify the existing gap and position the tools and methods presented.

3.2.2 Hypothetico-deductive method

All presented papers are contributing to the prescriptive study of the research by presenting new tools and methods. It can be hard to clarify what activities resulted in a new method or idea. Nevertheless, they should be based on experience and assumptions. A new hypothesis can be developed based on the existing literature and realizing the design process. In hypothetico-deductive method, a hypothesis can be formulated in a falsifiable form, by some experiments or observations where the outcomes are yet unknown [Johansson, 2003].

The main hypothesis in Paper A is that performing the selective assembly technique in multiple stages has the potential for obtaining assemblies with lower variations compared to the existing methods. The results of applying the presented method in two sample case corroborated this hypothesis. In Paper B, the hypothesis is that the quality of sheet metal assemblies can improve by utilizing selective assembly technique. This hypothesis is confirmed by applying the presented method to three industrial cases. In Paper C, the hypothesis is that modifying the mapping method to a one-to-one mapping method can improve the convergence rate of the optimization algorithm. Afterward, two sample cases are utilized to test this hypothesis. In Paper D, the hypothesis is that individualizing the locator adjustments leads to greater improvements compared to non-individualized adjustments. This is also confirmed by testing this hypothesis in three industrial cases.

3.2.3 Experiment

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

- Control of the researcher over independent parameters subjected to the experiment.
- The assignment of participants or objects to groups are on a random basis.
- The participants or objects can be considered to be representatives of the target population.

The research experiments are performed by manipulating the inputs of variation simulation models and observing changes in the outcome of simulations. In

Paper A, two assemblies from the literature are used and the presented hypothesis is applied to them to validate the hypothesis. The dependent parameter is the combination of mating parts and the outcome is dimensional variations of assemblies and the number of surplus parts.

Paper B utilizes three sheet metal assemblies to support the presented hypothesis. One of these sample cases has three components and the other two have two components. The reason is to check the validity for different numbers of components. The assemblies with two components also have a large difference in mesh sizes.

Paper C utilizes two sheet metal assemblies with a different number of components to assess the presented hypothesis about the convergence rate of optimization. Since the convergence is not always fixed and to some extent depends on random factors, the experiments are repeated 100 times for each case and trends and averages are considered for comparison. The same sample cases as in Paper B are considered for validating the hypothesis presented in Paper D.

The utilized sample cases in this research are not case studies because the Case Study method is descriptive in nature and there is no manipulation of the parameters. However, in the utilized sample cases there are always some parameters that are manipulated to assess their effect on the independent parameters, which are the main focus of the study.

CHAPTER 4

Results

This chapter provides a summary of 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 Paper A - Selective assembly of rigid parts

A major problem in performing selective assembly is mismatching. Different methods are presented in the literature to cope with this problem [Mansor, 1961, Fang and Zhang, 1995, Chan and Linn, 1999, Pugh, 1992]. The early studies mostly tried to generate groups of parts so that surplus parts were minimal. The recent studies try to utilize optimization algorithms in their methods to minimize the variation among all assemblies, in addition to surplus parts [Kannan et al., 2005, Kumar et al., 2009, Asha et al., 2008]. A common assumption in most existing methods in the literature is normal distribution of dimensions in the produced parts. Nevertheless, produced parts do not always have a normal distribution in their dimensions. Therefore, the methods that are based on this assumption may no longer be applicable to the problem.

There is only one study, [Kannan et al., 2009] that presented a method of solving the selective assembly where the normal distribution of parts was skewed. Paper A of this research presented a new method based on performing the matching in multi-stages without any assumption of the dimensional distribution of mating parts. The method presented in this paper tries to find the optimal combination of produced parts so that variation is minimal while surplus parts are zero. Figure 4.1 visualizes the algorithm presented.

Hence, after dividing parts into several groups with equal widths based on manufacturer preference, this algorithm finds the optimal combinations of groups. This combination of groups can be used for assembly until one group of parts

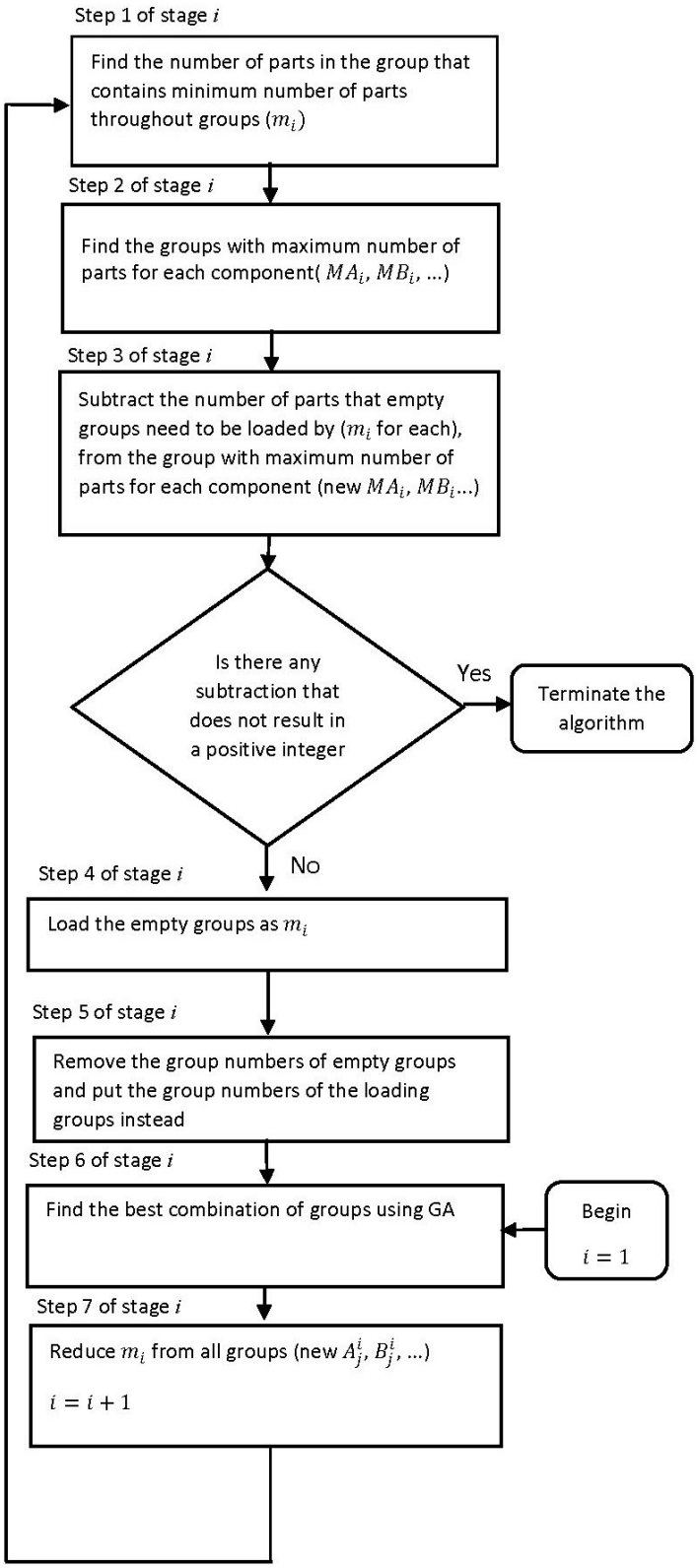

Figure 4.1: The presented algorithm for performing selective assembly in multi-stages [Rezaei Aderiani et al., 2018].

becomes empty. Thereafter, the next stage starts by borrowing some parts from the group with the highest number of parts for the empty group and finding the optimal combination again. This procedure continues until all parts have been utilized for assembly.

The previous method of performing the selective assembly for parts without normal distribution of dimensions has been applied to two sample cases and the results are available [Kannan et al., 2009, Wang et al., 2009]. Therefore, to evaluate the performance of the algorithm presented, it is applied to the same cases. The results show an improvement of 15% for the sample case in [Kannan et al., 2009] and a 20% improvement in the case presented by [Wang et al., 2009] in the variation of all assemblies compared with the previous method.

4.2 Paper B- Selective assembly of sheet metals

The target dimensions of some assemblies, including piston-cylinder or bearings, are simply a linear function of some dimensions of their mating parts. These types of assemblies are referred to as *linear assemblies* in this thesis. The literature study shows 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 is not reasonable to tighten the tolerances of mating parts.

New production lines have a higher level of automation. In addition, more inspection data are available. For instance, the deformed shapes of the produced parts can be determined by photogrammetry technique [Bergström et al., 2018]. Taking advantage of these availabilities, it is reasonable to apply the selective assembly technique to products such as sheet metal assemblies that are common in the automotive and aerospace industries. Xing and Wang [Xing and Wang, 2018] claimed, that they have 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 relation 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 mating parts. Consequently, their model is not applicable to real sheet metal assemblies.

Paper B addresses this gap and tries to fill it by presenting a new selective assembly technique for sheet metals. The final deviation of each assembly depends on the deviation of all points in mating parts and the deviation may not have the same pattern in all points of mating parts. Consequently, the preliminary question that this paper should answer is: Is it possible to improve the geometrical quality of sheet metal assemblies by selective assembly technique?

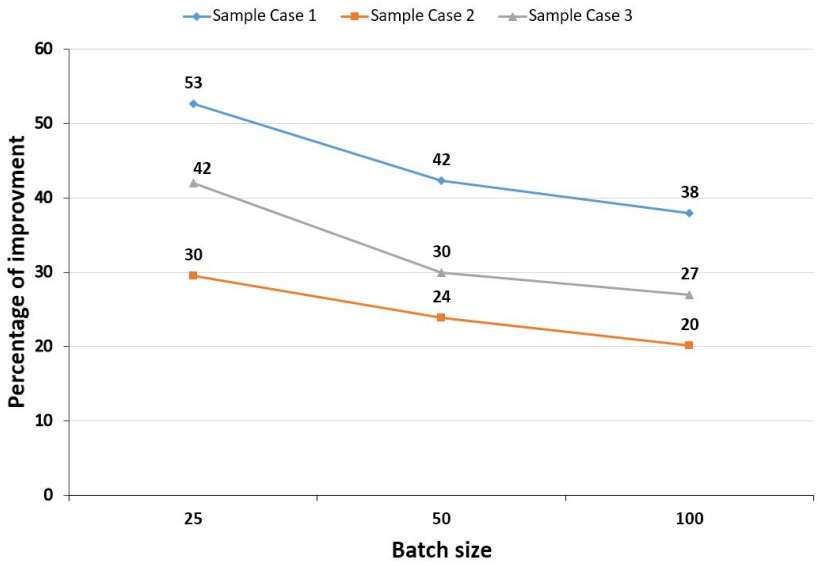

Figure 4.2: Effect of batch size on RMS_v [Rezaei Aderiani et al., 2019b].

There are three main differences 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 by changing the combination of mating 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 the assembly cannot correspond to only one or several dimensions from mating 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 summation or subtraction of some dimensions of mating parts. Instead, the assembly process should be simulated using CAT programs.

The method presented for the selective assembly of sheet metals is applied to three industrial cases for evaluation. The first sample case has three components and the other two cases have two components each. To evaluate the effect of batch size on improvements, three batch sizes of 25, 50 and 100 are selected for each case. Pareto Fronts are obtained and the percentage of improvements are calculated for every case and each batch size compared to the average RMS_v and RMS_m of 1000 random combinations.

Based on results, both RMS_v and RMS_m have improved for all cases. Hence,

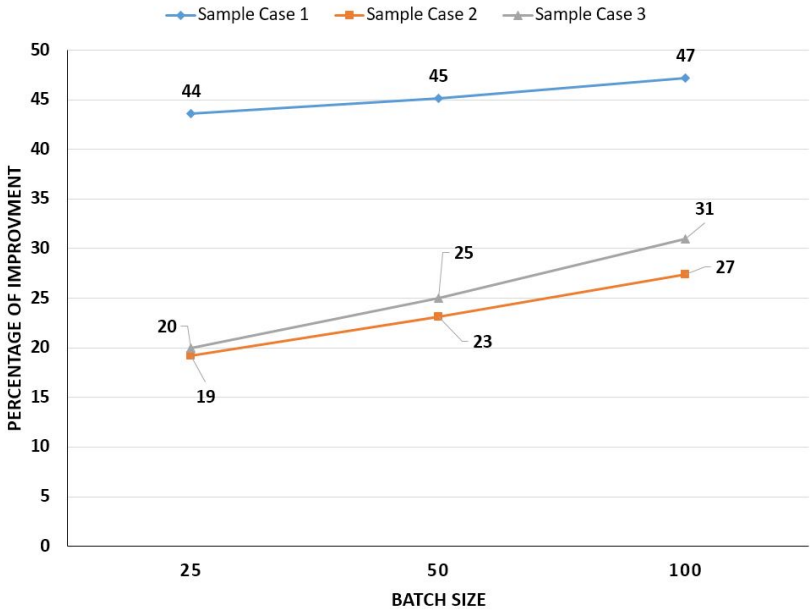

Figure 4.3: Effect of batch size on RMS_m [Rezaei Aderiani et al., 2019b].

the answer to the question about 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 improvement of RMS_m is greater for larger batch sizes whereas it is the opposite for RMS_v.

4.3 Paper C - Improving the convergence rate

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

To evaluate the effect of existing mapping, a one-to-one mapping is presented in Paper C. Thereafter, both mapping methods are applied to two sample cases from Paper B and results are compared. Since the population size is an important factor in the convergence rate, the optimization is performed for four different population sizes of 50, 100, 250 and 500 for each case. In addition, to avoid

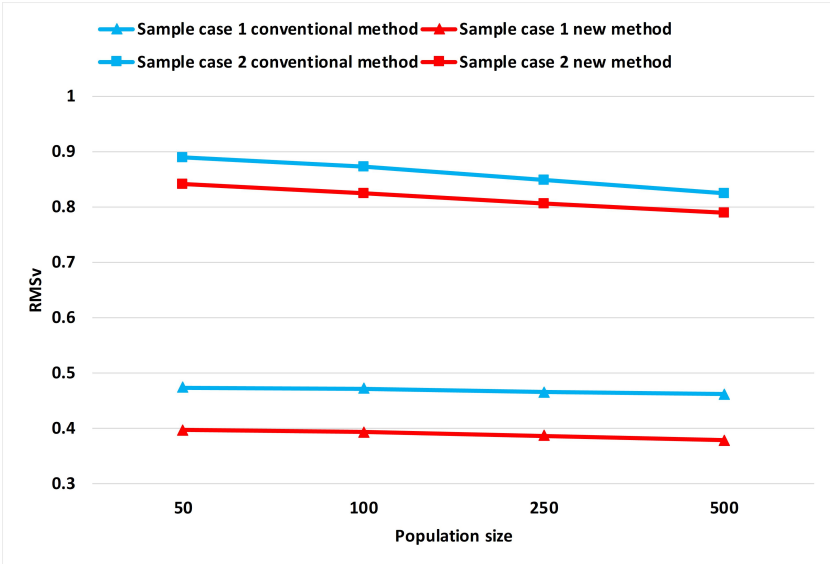

Figure 4.4: The average RMS_v obtained from both mapping methods for different population sizes [Rezaei Aderiani et al., 2019a].

the heuristic effects of the algorithm in results, each experiment is conducted 100 times and the average among them is calculated.

Figures 4.4 and 4.5 present the average RMS_v and RMS_m obtained using both mapping methods, respectively.

Based on the results, using the new method leads to finding better solutions (greater improvement in geometrical quality) on the average. In other words, the optimization algorithm has a better performance using the new method.

4.4 Paper D - Individualizing locator adjustments of assembly fixtures

Paper D of this thesis focuses on the individualization of the second technique, locator adjustments. Based on the literature studies in Paper D, there is a gap in studying of individualized adjustments for compliant assemblies. Thus, the results of both individualized locator adjustments and non-individualized locator adjustments should be evaluated and compared. Therefore, two methods are developed in this paper, a method for non-individualized adjustments and a method for individualized adjustments. The goal in individualized adjustments 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. To avoid undesired plastic

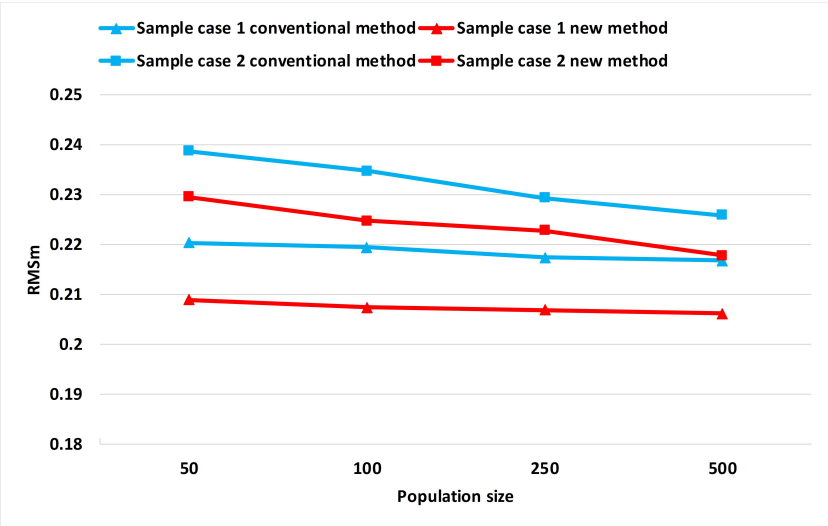

Figure 4.5: The average RMS_m obtained from both mapping methods for different population sizes [Rezaei Aderiani et al., 2019a].

deformations and residual stresses, two constraints are added to the problem that limit these two parameters during assembly.

The methods are applied to the three sample cases and the results are evaluated. To compare individualized and non-individualized adjustment with each other, the geometrical quality of each individual assembly and all assemblies together are presented. The criterion for the former is RMS_d and the criteria for the latter are RMS_m and RMS_v. Figures 4.6, 4.7 and 4.8 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 using a digital twin and not using it.

All assemblies have a greater geometrical quality when individualized adjustments are applied compared to when non-individualized adjustments are implemented. Besides, non-individualized adjustments have reduced the geometrical quality of some assemblies though the quality on the 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 D also presents a modification of the optimization algorithm that reduces the required adjustments for the same improvements.

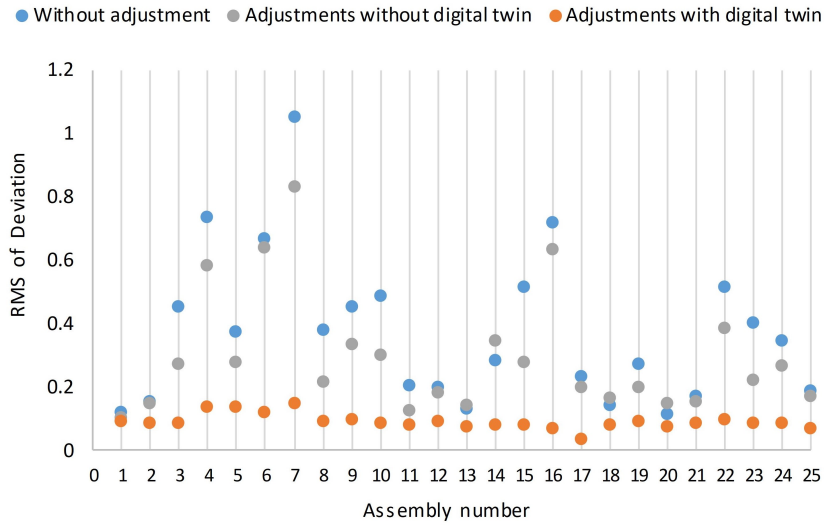

Figure 4.6: RMS_d of individual assemblies without adjustments, with non-individualized adjustments and with individualized adjustments for the first sample case [Rezaei Aderiani et al., 2019c].

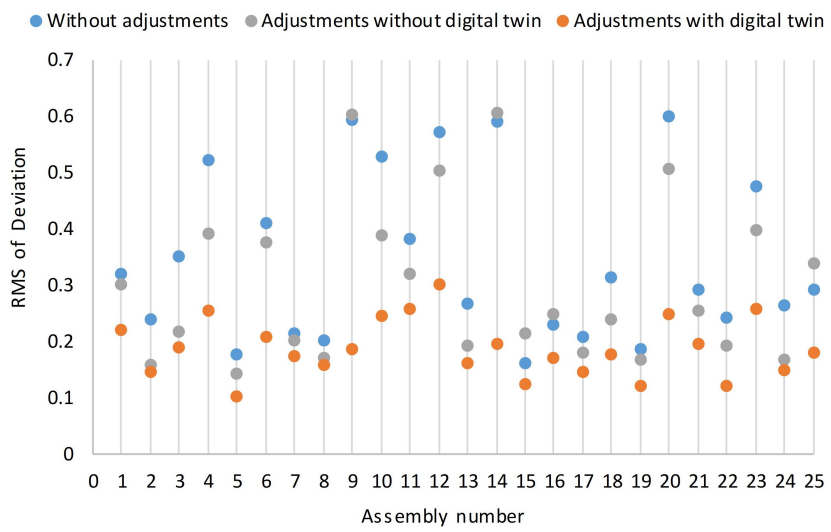

Figure 4.7: RMS_d of individual assemblies without adjustments, with non-individualized adjustments and with individualized adjustments for the second sample case [Rezaei Aderiani et al., 2019c].

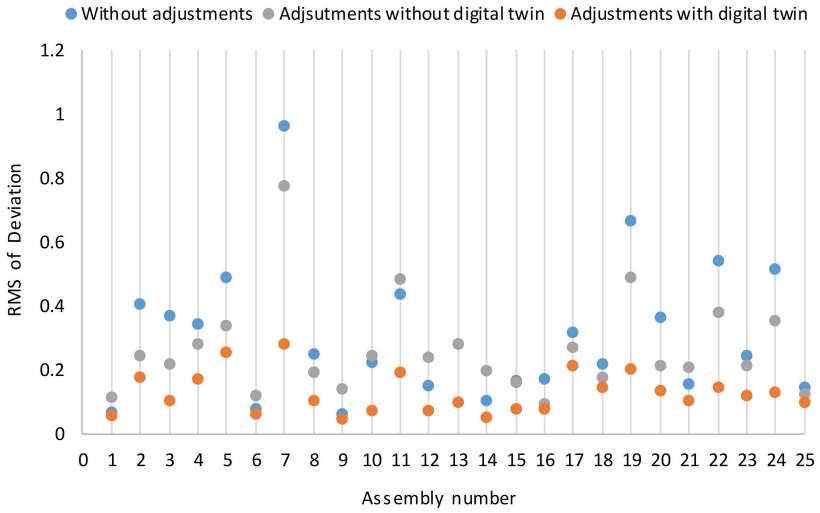

Figure 4.8: RMS_d of individual assemblies without adjustments, with non-individualized adjustments and with individualized adjustments for the third sample case [Rezaei Aderiani et al., 2019c].

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	
				Improvement [%]		Improvement [%]
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

CHAPTER 5

Discussion

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

5.1 Answering the research questions

RQ 1 *How can geometrical quality be improved by Individual Matching of parts?*

Three papers out of four in the thesis deal with answering the first research question. The literature studies in Paper A evidence that individual matching of parts, also known as selective assembly technique, is an old technique in the production of precise assemblies. These assemblies are linear assemblies where dimensional deviations of assembly have a linear relation with dimensional deviations in mating parts. Paper A adds a new method of performing selective assembly for linear assemblies to existing methods. The advantage of this method over other methods is that it can be applied to assemblies where dimensional distributions of mating parts are not exactly a normal dimensional distribution. In addition, it results in less variation compared with similar algorithms and no surplus parts.

Paper B illustrates that the existing methods of selective assembly are not applicable to nonlinear assemblies, including sheet metals. This paper propounds that it is not even clear if the selective assembly technique can improve the geometrical quality of sheet metals. This is because deviations of a high number of contact and welding points affect the deviations of the assembly and matching all those deviations for obtaining a better geometrical quality in assemblies may not be possible. Consequently, another question that is not answered in the literature is: Can individual matching of parts improve the geometrical quality of sheet metal assemblies?

Paper B develops a selective assembly technique for sheet metals. Thereafter, by evaluating the results of the method on three industrial sample cases, it answers the question raised about 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 geometrical quality can improve using individual matching of parts.

Paper B indicates that changing the batch size affects the improvements obtained from individual matching. Accordingly, it is required to clarify how the size of batch affects geometrical quality in order to answer how geometrical quality can be improved by individual matching of parts. Paper B conducts this clarification by comparing percentages of improvements in different batch sizes.

Paper B demonstrates that for problems with large sizes, it is not reasonable to find the optimal combination of parts using non-metaheuristic algorithms and metaheuristics including GA are preferred. Paper C unveils a problem in utilizing evolutionary algorithms to find the optimal combination of mating parts. This problem lies in the existing method of coding the phenotype to genotype and Paper C copes with it by developing a new method for mapping. The method presented improves the convergence rate of optimization and is a step forward in utilizing the selective assembly technique in a real-time control system.

RQ 2 *How can geometrical quality be improved by Individualized adjustments of locators of assembly fixtures?*

The improvement in geometrical quality by individualized adjustments of locators is studied in Paper D. In order to obtain an answer to the second research question, a method of performing individualized adjustments for rigid and compliant assemblies is required. The literature review in Paper D indicates that the aforementioned method has not been previously developed. Hence, Paper D develops a method of performing individualized adjustments without limitations on rigidity. Paper D 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 D 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 and up to three times greater than non-individualized adjustments. It is also evidenced that performing the adjustment, non-individualized may reduce the geometrical quality of some assemblies, whereas this problem does not exist in individualized adjustments.

Paper D adds another step forward in the answer to the second research ques-

tion by presenting a modification in the optimization algorithm utilized. Performing the modification results in obtaining the same improvements for fewer adjustments. This is important because it reduces the introduced stresses in the assemblies and adjustment work.

5.2 Scientific and industrial contribution

Individualized assembly processes have been limited to a few categories of products. However, due to recent advances in technology, it can be developed for more complex products. This research presents the potential for 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 the geometrical quality of their products or to reduce the production costs for the same geometrical quality.

The methods and tools developed in the appended papers contribute to filling the academic gaps in applications and studies of selective assembly and individualized adjustments. The contributions can be summarized as follows:

- Presenting a multistage method for performing selective assembly technique for linear assemblies with no dimensional distribution assumption. The presented method results in lower variation compared to similar methods and no surplus parts.
- Developing a selective assembly technique for sheet metal assemblies.
- Assessing the effect of batch size on geometrical quality improvements in selective assembly of sheet metals.
- Improving the convergence rate of optimization in solving selective assembly problem using metaheuristic algorithms by presenting a modification in the coding process.
- Studying individualization in locator adjustments of assembly fixtures by developing a method, applying it to industrial sample cases and assessing results.
- Presenting a modification in the optimization algorithm of individualized locator adjustments to reduce the required adjustments for the same improvements.

5.3 Validation and verification

Different methods are utilized to validate and verify this research depending on the type of study. Two methods of *logical verification* and *verification by acceptance* can be utilized to verify the results of research in design [Buur and Andreasen, 1990].

A research study is logically verified if its elements are consistent, coherent and complete [Buur and Andreasen, 1990]. There is no conflict among the obtained results of this research and the results support the same idea. Hence, they are consistent. For instance, the utilized sample cases for testing the methods developed in Paper A, Paper B, and Paper D approve the same conclusions about each method. The previous observations are approved by the presented methods and tools which is shown in literature studies of all papers and illustrates the completeness of results. The presented results are continuations of the previous studies which illustrates the coherence of the results.

The results are also verified by acceptance. The appended papers have been peer-reviewed by experienced designers and scientists in the field and accepted. Moreover, the research has been conducted in close cooperation with experienced designers and researchers.

Validation and verification are also performed in different stages of research. The validity of the defined problem and research questions are approved through the performed literature reviews. A developed method or tools can be validated by *comparison to other models* and *face validity* based on [Sargent, 2010]. Face validity is the same as *verification by acceptance* which is performed for all models and the presented models and methods are compared to other similar approaches if they exist.

This study has utilized modeling and simulation to verify the developed tools and methods. The utilized sample cases should be valid for performing an experiment on the developed methods and tools. For instance, the sample cases in Papers B and D should represent a real sheet metal assembly in industry. Therefore, to have valid sample cases, the models are taken from the automotive and aerospace industries.

The validity of modeling and simulation of the presented sample cases have been checked by different methods, including *animation*, *comparison to other methods*, *parameter variability- sensitivity analysis* and *trace* methods [Sargent, 2010]. For instance, the size of the mesh and number of contact elements are verified by sensitivity analysis. The models are simulated by coarser and finer mesh size and results are compared with the mesh size utilized. Since the differences in results are lower than considered accuracy in the simulation, the meshing is verified.

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 not sufficient scanned data of parts to import them, the deformed parts are only generated randomly by Monte Carlo simulations. Using these parts as deformed parts is verified by generating the color coding of their variation and comparing them with those that are obtained from physically produced parts. Moreover, checking the graphs of the generated deformed parts can show if they are continuous and within the range of defined tolerances.

5.4 Future work

The results of this research evidence the great potential of selective assembly and individualized adjustments of locators. These techniques were studied separately in this research. Nevertheless, the proposed concept of Smart Assembly 4.0 considers performing both these techniques on an assembly line. Therefore, the combination of these techniques will be studied together in future research.

In addition, performing individualized locator adjustments in the assembly process of a product can change the criteria of designing its locating scheme. An important criterion in designing a locating scheme is to have minimal sensitivity to the variation of locators. Nevertheless, if the locators are supposed to be individually adjustable, it can be desirable to have a locating scheme that is more sensitive to locators. This is an important subject to be studied in future research.

CHAPTER 6

Conclusions

In this research, ways of improving the geometrical quality by individualizing the assembly process were studied. The focus was on two techniques of individual matching of parts and individual adjustments of locators. The existing methods of performing these techniques were studied, gaps were found and methods and tools were 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 that are drawn in the context of selective assembly are listed as follows:

- The improvement by the selective assembly for rigid and linear assemblies covers only dimensional variation, whereas for sheet metals both dimensional variation and mean deviation can improve.
- Utilizing the method presented of performing a selective assembly for linear assemblies results in lower variation compared to other methods and no surplus parts. The dimensional distribution of mating parts is not required to be normal for performing the method presented.
- Increasing the batch size in sheet metals leads to increasing the percentage of improvement in the mean deviation but reducing the percentage of improvement in variation.
- Utilizing the presented method of mapping from phenotype to genotype in Paper C improves the convergence rate of optimization.

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

- Performing the 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 quality of all assemblies improves in on the average. However, the individualized adjustments improve the geometrical quality of all assemblies.
- Utilizing the presented modification in Paper D about optimization algorithm results in reducing the required adjustments for the same improvements.

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Paper C

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