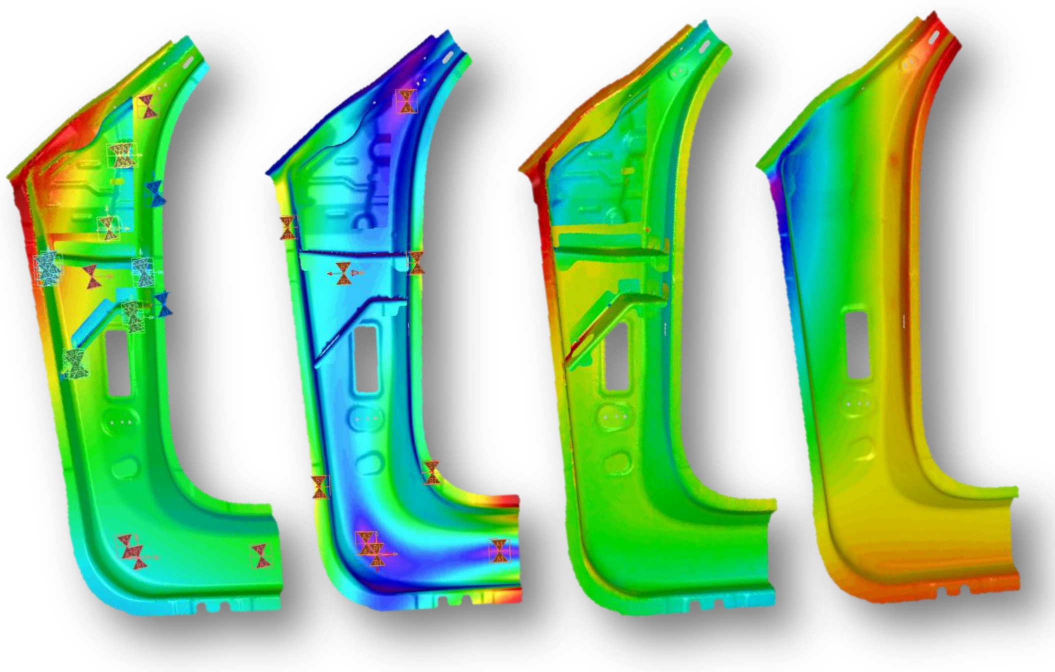

Non-Rigid Sheet Metal Assembly Simulation and Selection of the Geo-Spots for Further Optimization

Master's Thesis in Production Engineering

JIE SHAO

ROHAM SADEGHI TABAR

Department of Product and Production Development
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Technical report no xxxx:xx

Department of Product and Production Development

Division of Production Engineering

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Cover:

[The picture displays four simulation models that are developed for Case A in the report. The color plots are generated by RD&T software]

Gothenburg, Sweden 2014

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Writing a master thesis is like a long journey where everything can change in a moment. During this journey we had a lot of fun, but also many moments of doubt and uncertainty. Fortunately, we were not alone during our journey. That is why we would like to thank all the people who helped us with this complicated process of thesis creation.

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Jie and Roham

Non-Rigid Sheet Metal Assembly Simulation and Selection of the Geo-Spots for Further Optimization
Master's thesis in Production Engineering

JIE SHAO
ROHAM SADEGHI TABAR
Department of Product and Production Development
Division of Production Engineering
Chalmers University of Technology

Abstract

This thesis work presents research about robust solutions for non-rigid sheet metal assembly simulations in collaboration between Chalmers Wingquist Laboratory and Volvo Car Corporation in Gothenburg, Sweden. The purpose of this project is to develop a valid strategy for classifying geo-spots and respots of non-rigid sheet metal assembly. The goal of this project is to establish an effective method to select geo-spots in order to increase the geometry robustness of an assembly. Moreover, the method should facilitate the work of balancing the respot points and lowering their influence on geometric variance.

To achieve the goals, industrial experience of selecting geo-spots was acquired by a comprehensive interview approach that was designed to obtain both tacit and explicit knowledge of the interviewees. Experts within geometry field from both Chalmers and VCC together with participants from Volvo Trucks were involved in this project. A method based on the multi-criteria decision making approach AHP (Analytical Hierarchy Process) was utilized to analyze the empirical data. Furthermore, a *Geo-spot Selection Workflow* (*GSSW*) was formulated, describing the experiential approach towards the task of selecting geo-spots.

Finally, a new method combining *GSSW* and computational analyses was proposed. The method also utilizes the decision making approach, AHP, for selection of the best geo-spot set. With this comprehensive method, instead of only depending on engineering experience, the diagnosis of the geometry problems can be made by using the computer simulations. In addition, assembly errors can be visualized in simulation software to support decision making. Two industrial cases were analyzed by using the computer aided tolerance (CAT) tool RD&T. The simulation results verified that the proposed method can assist the decision making of choosing suitable spot-welds on the assembly.

Keywords: geo-spots, respots, non-rigid sheet metal assembly, spot welding, compliant analysis, AHP

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BIW	Body in White
CAD	Computer Aided Design
CAT-tool	Computer Aided Tolerancing - tool
CF	Consideration Factor
CG	Classification Group
CM4D	Coordinate Measurement Machine Management Mechanism for Data, a database for storing and a tool for analysis of geometric measurements at VCC
ENM	Elastic Net Method
FEA	Finite Element Analysis
GA	Genetic Algorithm
GSSW	Geo-Spot Selection Workflow
MCS	Monte Carlo Simulation
MIC	Method of Influence Coefficients
RD&T	Robust Design and Tolerancing, a CAT-tool.
RMS	Root Mean Square
RSS	Root Sum Square
SI-GSSW	Simulation Integrated - Geo-Spot Selection Workflow
VCC	Volvo Car Corporation
WP	Welding Point
WPP	Welding Process Parameters
WPR	Welding Process Restrictions

1. INTRODUCTION

This chapter describes the purpose, the goals of the project and the main problems occurring in the industry. The delimitations and the sustainability aspect of the project are also presented. Lastly, the outline of this master thesis report is presented.

1.1. Background

The Body in White (BIW) of a car is assembled using many sheet metal parts with different geometries. A joining process is always included in non-rigid sheet metal assembly procedures. Most of the joints between parts are made by spot-welds in this process. In a vehicle body, there are more than 4000 spot-welds which join the metal parts together [1]. For these assemblies, geometry variation in the parts and in the manufacture process will result in variation of the final product or the sub-assembly [2]. Söderberg et al. identified that, three contributors, part variation, assembly variation and design concept, are the main causes of geometrical variation [3]. Understanding and testing the consequences of those contributors virtually can facilitate robust solutions earlier in the product development phases (see Figure 1). More robust solution can contribute to minimize the lead time and cost of physical matching and trimming activities [4, 5, 6]. To achieve geometry solutions that are insensitive to variations and disturbances, the tools and methods for assuring the geometry robustness of sheet metal assemblies are desired within automotive industry [5].

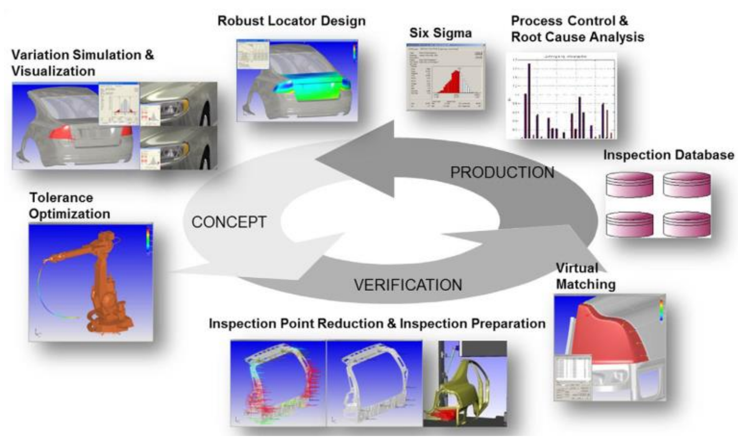


Figure 1: Geometry assurance activities in different product realization loop [3]

Volvo Car Corporation (VCC), a manufacturer of cars in the premium segment, aims at assuring the geometry of the product and ascertaining robust solution as early as possible in product realization loop. The final assembly of BIW consists of many pre-assemblies in which geometry variations will be stacked to the succeeding assemblies [5]. There is a need for research to propose a method of selecting geometry points[1] to lock the geometry of the assembly in pre-assembly stations and minimizing the influence of later respot[2] processing. The main work of this project is conducted at VCC, Sweden.

The assistance of computer aided tolerancing tool (CAT-tool) is increasingly important to establish and verify a robust solution. Söderberg et al. [5] argue that the usage of CAT-tool will ease the analysis of

[1] Geometry points are referred as geo-spots.
[2] Respots are the spot-welds welded after geo-spots in the succeeding stations.

design to ascertain whether a robust solution is achieved to withstand the influences of the manufacturing process. Moreover, with help of these CAT-tools, verifications and modifications of the product and the assembly process can be visually supported in a virtual environment.

The CAT-tool RD&T (Robust Design and Tolerancing) is utilized to model the assembly of non-rigid parts and analyze the geometric robustness of the non-rigid assembly process in this project. RD&T is a software package that supports the geometry assurance process in all phases, concept, verification and production (see Figure 1) [5, 7]. The functionalities for compliant analysis in RD&T are stability, contribution and variation analysis. Stability analysis is used to find a robust locating scheme. Contribution analysis is used to analyze the contribution of the specific locating or contact points and other tolerances on important features to the final assembly variation. Variation simulation is used to analyze the geometrical outcome of the assembly. The consequences of modifications in parts and tooling can be demonstrated and visualized in RD&T to support the decision making.

1.2. Purpose

The purpose of this project is to investigate the current working procedure of selecting geo-spots in non-rigid sheet metal assembly. In order to increase the geometrical robustness and to reduce the lead time, a standardized method for selection of geo-spots should be established. The method is required to ease the selection of the suitable geo-spots in order to reduce the number of the weld points included in the sequence analysis.

1.3. Goals

Establishing a systematic method to select geo-spots in non-rigid sheet metal assemblies is the main goal of this project. The proposed method should consider the factors influencing the selection of geo-spots. The identified factors should be ranked by their importance in the decision making.

The method should provide guidelines for choosing the geo-spots on parts. Through implementing this method, reduction of geometrical deviations will be facilitated and geometry robustness can be assured. It should also provide a standardized operation procedure that can shorten training time for the engineers in this field.

In addition, the method should facilitate the work of balancing respots and lowering their influence on the geometrical outcome. Lastly, a set of potential improvements in the area of geo-spots selection using simulation needs to be proposed.

1.4. Objectives

To achieve the goals, detailed objectives were set and divided into three areas:

1. **Theory foundation.** Firstly, previous research about selecting spot-welds should be investigated in order to build-up theory support for geo-spot selection. Variation simulation of non-rigid sheet metal assemblies should be analyzed to understand the theories behind the functionalities of the CAT-tools RD&T. Secondly, the factors influencing the final assembly variation in previous research should be summarized. Lastly, a scientific method for multi-criteria decision making needs to be suggested to make a decision model.

2. **Industrial work routine.** Firstly, a comprehensive interview strategy should be developed to acquire both explicit and tacit knowledge from interviewees in industry. Secondly, the target interviewees who are experienced in the geometry assurance area need to be identified and interviewed. Lastly, the current work routine of choosing geo-spots in the company should be described.

3. **Simulation and analysis.** Firstly, suitable industrial cases should be prepared and modeled in the CAT-tool RD&T. Secondly, an approach of selecting geo-spots based upon simulation results needs to be proposed. Lastly, a comprehensive work procedure should be presented that integrates the industrial work routine and virtual testing and verification by simulations.

1.5. Problem description

The main problem is:

How to formulate a comprehensive work procedure for selection of geo-spots in non-rigid sheet metal assemblies, which integrates industrial routines and simulation approaches?

Moreover, there are some other sub-problems that need to be considered while solving the main problem, including:

- What are the main factors influencing the selection of geo-spots?
- What is the current work routine in the industry to select geo-spots?
- How can variation simulation tools be used in order to support the selection of geo-spots?

1.6. Delimitations

The project has only focused on the welding process in a pre-assembly station at VCC due to the complexity of the task. The pre-assembly station consists of a geo-station and a respot station. In this process parts are firstly loaded to the fixture, clamped and welded in geo-station. After this step, the assembled part will be released from the fixture, fetched by a gripper and finally respot is performed under a fixed gun. The discussion about selecting geo-spot is based on two specific case scenarios which will be presented in Section 3.4.

The method of selecting geo-spots is tested by conducting variation simulations in the CAT-tool RD&T. In this simulation, the part deformations and process deviations from nominal are assumed to be small. Therefore, the stiffness matrices can be calculated based on nominal shapes and the part deformations are assumed only to occur in the elastic area [8]. Lastly, thermal deformation caused by the welding process, will not be taken into consideration in the herein presented studies.

1.7. An insight to sustainability aspect

This project not only focuses on the hard technical aspects of the engineering work, but also in a broader perspective it contributes in building a sustainable future. Considering different levels of sustainability, the project goals and objectives intend to improve sustainability in three aspects, namely environmental, social and economic sustainability [9]. In an environmental point of view, a virtual study of the assemblies before physical trials help to reduce waste in form of scrapped material involved in the assembly process. The introduction of a working method to ease the decision making in the multidisciplinary task of geo-spot selection and adding the simulation support will help to decrease cognitive limitation for the employees in the related areas. Moreover, by using simulation software, personal safety for the workers can be improved while there is less human intervention with the physical parts and tooling elements in the process. Finally, reducing the lead time and calculation time required for optimization of the sequence of the spot welds will help to reduce the cost of the process. In addition, through applying the simulation tools less tooling is required for physical verification which means reduced engineering waste, less scrap and less cost. Therefore, economical aspect of sustainability will also be taken into consideration.

1.8. Outline of the report

Chapter 1 states the background of the project, purpose, goals, objectives and problem description, which elaborates each task in the project. Chapter 2 presents the theory about geometry point selection and variation simulation in non-rigid sheet metal assembly, and describes the facts about spot-welding process. The theory of multi-criteria decision making approach used in this project is also presented. Chapter 3 describes the methodology applied in this project, the strategy of the interviews and cases studied in this project. Chapter 4 presents the results of the interviews and also a set of hypotheses that are verified during the interviews. Chapter 5 presents the proposed method of geo-spot selection, the results of simulation and the made geo-spot selections in the two studied cases. Chapter 6 presents a list of results achieved in this report. Chapter 7 discusses the results of the project and possible future research. Finally, in Chapter 8 the conclusions drawn from this work are summarized.

2. THEORY

This chapter presents some of the previous research about selecting spot-welds and variation simulation of non-rigid sub-assemblies. In addition, the applications of the variation simulation methods in the spot welding process and the factors influencing the variation of non-rigid sheet metal assemblies are described. Furthermore, theories related to spot welding sequence optimization strategies are also given. Lastly, a multi-criteria approach for decision making adopted in this project is elaborated.

2.1. Previous research

Enhancing geometry assurance of BIW is increasingly concerned in automotive industry. Most of the research in the field of robust design attempt to utilize variation simulation software to minimize the assembly variation. The proposed methods in the previous studies mostly establish strategies for selecting spot-welds based on certain criteria. The main contributors of geometrical variation have been identified as part variation, assembly variation and design concepts [3]. Further research about evaluating the effect of those factors on complaint part and taking them into account in variation simulation has been conducted, for instance by Söderberg et al. [5].

Strategies of selecting spot-welds for a sub-assembly have been investigated. Liao [10] presents a Genetic Algorithm (GA) based method, to select the number and the locations of the weld spots, which automatically searches for the best spot-weld candidate to meet the designed objective function. The used objective function takes the sum of the user-defined weight factors multiplied by deformation and/or the variance of deformation in the weld points. The proposed method was tested in a case study [10].

Yang and Shao [11] present a strategy to minimize cycle time and distortion that arises from the welding thermal load. In order to minimize cycle time, they generate the optimized welding path using on elastic net method (ENM) [12]. Distortion values are derived from a thermo-mechanical model, indicating the importance of each welding point. The proposed strategy is successfully carried out on a real product [11].

Wärmefjord et al. [2] distinguish a set of special weld spots from other spots in the assembly. Geo-spots are the spot-welds locking the geometry of pre-assemblies. If such set of geo-spots is selected to secure the geometry of the pre-assemblies, then they can be released from fixtures and welded by respots in succeeding stations.

These previous research have proposed some methods to take the influence of selecting spot-welds. However, there is still a lack of a verified method describing how to select spot-welds to minimize geometrical variation of assemblies. The geo-spot is usually selected based on engineering knowledge and experience rather than the selection based on simulation support within automotive industry. If the geo-spots can be selected appropriately, the geometric stability can be improved. The balancing of the respot points can then be done freely based upon available cycle time. The aim of this work is to find a valid strategy for identifying geo-spots to reduce geometrical variation in the final assembly.

2.1.1. Variation simulation for non-rigid parts

The most commonly used variation simulation methods are based on worst case tolerance analysis, Root Sum Squares (RSS) and Monte Carlo Simulation (MCS). These methods are applied to sheet metal assembly processes mainly under the assumption of rigid parts [13]. The traditional variation analyses of rigid parts consider the final assembly variation to be determined by geometric and /or kinematic relations [13]. Liu and Hu [14] developed an *offset finite element* method to predict the assembly variation by integrating engineering structural models with statistical methods to analyze the variation accumulation. However, in reality, sheet metal assemblies consist of deformable parts (non-rigid parts). As a consequence, the part variation does not stack up as these methods predict.

The non-rigid parts are also affected by the interaction among the parts and the locating schemes. To analyze non-rigid sheet metal assembly, most of the methods are based on the Finite Element Analysis (FEA). The parts within the assembly are firstly meshed in order to be used in the FEA calculation. The assembly variation is simulated by applying forces to the geometry mesh and these force results in node displacements [15]. Liu and Hu [13] discuss the drawback of using Direct Monte Carlo Simulation method. In each MCS-iteration, a new FEA calculation will be conducted, which takes tremendously long computational time. A more efficient method is required to analyze complex assemblies. Therefore, Liu and Hu [13] proposed Method of Influence Coefficients (MIC). The key to the MIC method is to establish a *mechanistic variation model*, which is a linear relationship between the part deviations and the assembly spring-back deviations.

One disadvantage of MIC is that the parts in the assembly are allowed to penetrate each other, which will affect the accuracy of variation simulation. To resolve this issue, Dahlström and Lindkvist [16] propose a contact algorithm that is combined with MIC to avoid the penetration between the adjacent parts. A node-surface calculation is performed to determine whether there is penetration. The penetrated nodes will be forced out of penetration by applying contact reaction force. These forces are determined by an iterative process.

A slightly modified version of the contact modeling method is presented by Wärmefjord et al. [15]. The automatic contact detection is implemented, which considers the node-node contacts instead of node-surface contacts as in Dahlström and Lindkvist's method [16, 15]. The modification of contact modeling makes the algorithm to become faster, while somewhat less accurate. However, the case studies executed by Wärmefjord et al. prove that the simulation results of the modified contact modeling method are still significantly better than not using contact modeling [15]. To further reduce computational efforts and time, Wärmefjord et al. [15] also proposed a procedure to reduce the number of contact pairs not to be closer than a certain distance along the flange.

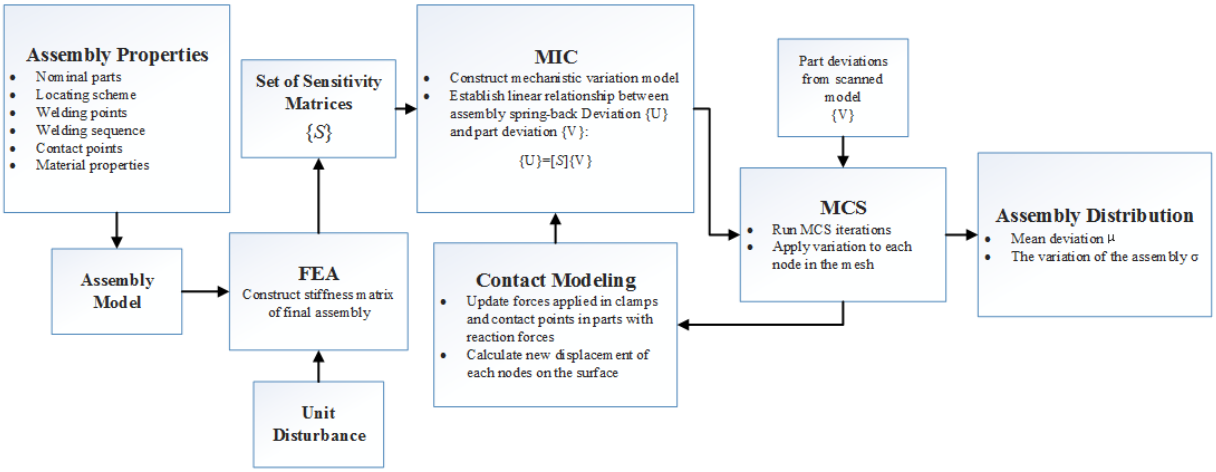


Figure 2: Variation simulation procedure [12, 16, 15]

The variation simulation procedure that is concluded from the previous theories is presented in Figure 2 and the whole process is realized in the CAT-tool RD&T. This procedure is utilized to conduct variation simulations for the case studies in this thesis. The part deviation obtained from scanning of real parts will be used as input to the variation simulation. Unit disturbance is used in FEA to construct the needed sensitivity matrices. Extra sensitivity matrices are used in each MCS iteration to resolve the contact modeling.

2.2. The spot welding process

In this section, a pre-assembly station of the spot welding process in automotive industry is elaborated. As already mentioned, the complete car body assembly is made out of many sheet metal sub-assemblies. A sub-assembly can be built in a pre-assembly cell. This cell can contain a geo-station and a respot station (see Figure 3). In this report, geo-spot selection refers to the selection of the spot-welds in the geo station in the pre-assembly cell.

Figure 3 presents a scenario of the work procedure in such a cell. In the geo-station, the parts are firstly positioned in the fixture and then clamped to hold the parts in position. The next step is joining, which in this case is spot welding of the geo-spots, to lock the geometry. After the welding step, the assembly is released from the clamps. Afterwards, the assembly can be handled by a gripper that will fetch the assembly from the geo-station's fixture and will hold the sub-assembly during the respot. In the respot station, the remaining spot-welds on the assembly (the so called respot points) will be welded. The detailed information about the welding procedure will be described in Section 2.2.1.

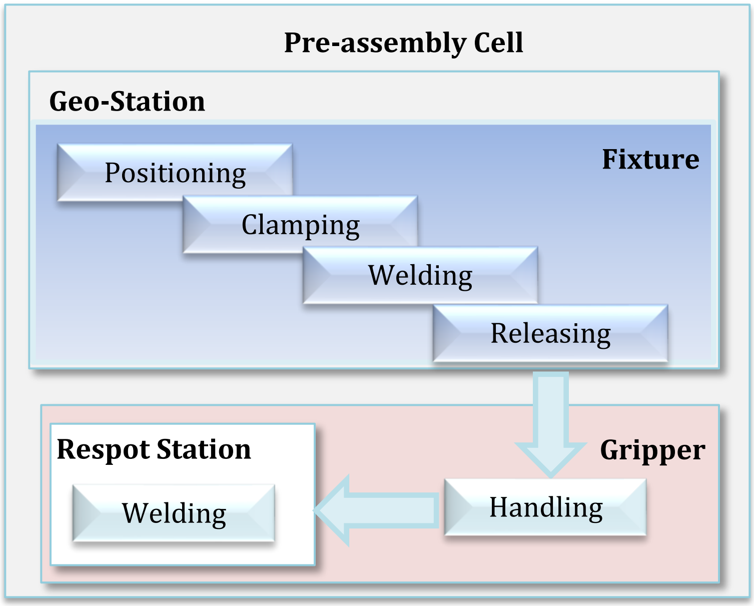


Figure 3: A pre-assembly station in automotive industry

There are two types of welding guns that can be used in such cells, namely a balanced gun or a position gun. The welding gun used at geo station is a balanced gun. For a balanced gun, equal forces are applied on the surfaces to force the parts together. Then, the sheet metals will meet in a position of equilibrium [2].

The welding gun used at the respot station is a position gun. In this type of gun, the surfaces are force to a fixed position. Both of these types of guns have two electrodes applied on both side of the part. When the gun closes, an electric current will be applied fusing (melting) the parts together [2].

2.2.1. Factors affecting assembly variation in welding process

This section summarizes the previous research regarding the factors affecting final assembly variation of welding process. These factors influence the selection of geo-spots [5, 4, 2, 17] (see Figure 4). The design concept has a significant influence on the final assembly variation. To minimize the influence of these variations a robust design is sought [5, 18]. Moreover, part deviation might be caused by unstable previous processes. Material properties of the part such as material characteristics, thickness and spring back effects also have influence on the part deviations [2, 5, 19]. The manufacturing process of an assembly, including fixture variation and welding variation, will also contribute to the final assembly variation. Fixture variation and welding variation are summarized in terms of the welding process related to the fixture of assembly and the welding equipment used in production [5, 19]. Figure 4 depicts various contributors to final assembly variation [19].

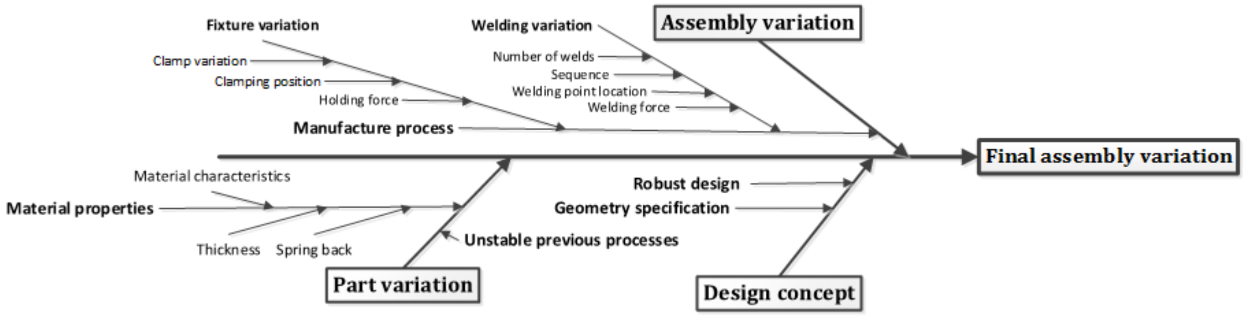


Figure 4: Contributors of final assembly variation [14]

The assembly of a sheet metal structure can be divided into the following steps:

(1) ***Positioning*** — the parts are loaded by a gripper or manually into the positioning fixtures.

(2) ***Clamping*** — when the clamps are closed, the parts are forced into the position defined by the locating schemes. With over-constrained locating schemes, the parts are bended and deformed by the fixture. Mating surfaces come in contact and the initial gaps between the mating surfaces are closed by clamps [2, 5, 20, 19].

(3) ***Welding*** — the parts are welded together. If there is a gap between the parts, they are forced together by the welding gun. These deformations build up internal residual forces within the assembly which will cause spring back of the sub-assembly when released from clamps. The sequence of the welded spots has a great influence on the geometrical deviation in the final assembly [2].

(4) ***Releasing*** — the parts are released and spring back occurs due to the built in tensions and stresses during the clamping and welding steps. The geo-spot set welded, whilst the parts were clamped, shall reduce the effect of spring back and assure the geometry accuracy [2, 19].

(5) ***Handling*** — the sub-assembly is fetched from the fixture by a gripper. The gripper is holding the sub-assembly during the succeeding process. The previous set of geo-spot should secure the rigidity of the assembly to withstand forces from handling and forces applied when the assembly is fetched by the gripper.

(6) ***Respot process*** — the assembly is held by a gripper and the respots are welded. The influence from the respots on the geometry of the assembly should be minimized.

(7) ***Release from gripper*** — the assembly is released from the gripper and handled to subsequent processes. At this step a minimum amount of spring back is desired.

2.2.2. Simulation of spot welding process

Wärmefjord et al. [4] have shown in their study that the above work procedure of spot welding process taking the spot welding sequence into account can be sorted in three main steps of the calculation in variation simulation [4]. In this way, part stiffness and clamping forces can be included in compliant analysis to handle part deformation and spring back in assembly. The following formulation is summarized from Wärmefjord et al. study [4]:

First Step: *Positioning and clamping*

The two parts (A and B) are positioned in their fixtures and over-constrained locating systems are applied. Over-constrained locating systems are allowed in the process due to the fact that in non-rigid analysis parts can bend and deform during positioning.

The vectors $\{u_p^A\}$ and $\{u_p^B\}$ represent the gaps that are going to be closed in the clamping points. To close the gaps, forces $\{F_p^A\}$ and $\{F_p^B\}$ are applied to the parts respectively. $[K_p^A]$ and $[K_p^B]$ represent the stiffness matrices. Then the following relations hold:

$$\{\boldsymbol{F_p^A}\} = [\boldsymbol{K_p^A}]\{\boldsymbol{u_p^A}\} \quad (1)$$

$$\{\boldsymbol{F_p^B}\} = [\boldsymbol{K_p^B}]\{\boldsymbol{u_p^B}\} \quad (2)$$

Second Step: *Welding when sequence is taken into account*

To set welding point ***i =1,...,N***, a force $\{\boldsymbol{F_a^i}\}$ is applied. In this formulation index ***a*** stands for assembly.

$$\{\boldsymbol{F_a^i}\} = [\boldsymbol{K_a^{i-1}}]\{\boldsymbol{u_a^{i-1}}\} \quad (3)$$

Here, $[\boldsymbol{K_a^i}]$ is the stiffness matrix describing the assembly after welding point ***i***. These stiffness matrices are defined to calculate the spring back. During the process, after welding point ***i*** is set on the assembly, it is released from the fixture and therefore spring back will occur. After occurrence of spring back, the assembly is positioned and clamped again. The force $\{\boldsymbol{F_a^i}\}$ including both the updated clamping forces and the reaction forces to each node due to contact modeling is applied. Contact modeling forces are taken into consideration due to the fact that during virtual assembly, there is a risk that the parts penetrate each other, which is not the case in reality.

The new stiffness matrices are generated for every new welding point by adding a new matrix $[\boldsymbol{K_{wp\,(iA,iB)}^i}]$, locking all degrees of freedom corresponding to the added welding point, to the previous stiffness matrix. Therefore the following holds:

$$[\boldsymbol{K_a^i}] = [\boldsymbol{K_a^{i-1}}] + [\boldsymbol{K_{wp\,(iA,iB)}^i}] \quad (4)$$

Knowing the force and the stiffness in each step then the deviation from nominal after adding welding point *i*, $\{\boldsymbol{u_a^i}\}$, can be calculated.

Third Step: *Releasing*

After completing welding of the points, the assembly will be detached from the fixture and spring back will occur. Forces $\{\boldsymbol{F_a}\}$ corresponding to the reaction forces in the clamps can then be calculated as follows:

$$\{\boldsymbol{F_a}\} = \{\boldsymbol{K_a^N}\}\{\boldsymbol{u_a}\} \quad (5)$$

Later in the spot welding process the handling variations can be simulated by introducing disturbances to the assembly's gripper position and the respot welding step can be simulated with the aforesaid three steps.

2.2.3. Influence of spot welding sequence

The sequence of spot welding cannot be ignored and has proven to have significant influence on assembly variation and spring back effects after tool release [10]. To minimize the geometry variation, some studies have been conducted to find the optimal sequence of the spot welds. Wärmefjord et al. describe several methods of assigning welding sequence such as: general simple guidelines, minimizing variation in each step, sensitivity and relative sensitivity methods [2]. Segeborn et al. evaluate GAs on welding sequence with respect to dimensional variation and robot cycle time [1].

To find the optimal welding sequence, the current work method is to try different combinations using GAs and some previous case studies have verified that GA method generates promising results [2, 10, 17, 1]. However, finding the optimal sequence while there is large number of spot-welds on the assembly would be a time-consuming task. If there are *N* spot-welds in the assembly, *N* points will have *N!* possible sequences (e.g. $8! = 40320$) [2, 17].

To resolve the problem of long computational time, the spot welds can be classified into geo-spots and respots in the welding process prior to assigning the welding sequence. As long as the selected k geo-spots lock and secure the geometry of the assembly, the welding sequence of *N*-*k* respots can be assigned by any sequences and they will still have a low influence on the geometry of assembly. Then, the amount of calculation in GAs will be reduced to investigate *k!* possible combinations for geo-spots [2, 17].

2.3. Decision making approach

In order to assign all the spot-welds on the assembly to geo-spot and respot sets, the identified contributing factors (see Section 2.2.1) should be taken into consideration. A scientific method for analyzing the importance (weight) of each factor is required. Applying the results of the interviews, a working procedure is presented for selecting different sets of geo-spots. Thus, a decision making approach is needed to evaluate the proposed sets of the geo-spot sets based on the criteria presented in Section 3.2.

Analytical Hierarchy Process (AHP) is a multi-criteria decision making method. It is an Eigen-value approach to perform pair-wise comparisons. This method also calibrates the numeric scale for the measurement of quantitative and qualitative performances [21]. The ratio scales are derived from paired comparisons, which represent people's subjective reflection, such as the relative strength of preferences [22, 23]. The most effective way to make a judgment is to take a pair of elements and compare them by a common criterion without other elements [22]. The paired comparison is the core process of AHP. These comparisons applied to each element on every level within the hierarchy (see Figure 5).

To implement AHP analysis, a hierarchic structure has to be built to display the problem (see Figure 5 and 6) [22, 23]. The hierarchy clarifies the relations among all criteria and sub-criteria that make up the problem. The top level describes the overall goal and the next levels should contain all the criteria that are contributing to the goal [22]. With the help of this structure, the overall goal can be broken down into detail on each level.

In general, there are two types of AHP measurement; absolute and relative measurement [22]. Both of them derive weights by executing paired comparisons with respect to the overall goal. The Sections 2.3.1 and 2.3.2 describe each.

2.3.1. Absolute measurement

In absolute measurement paired comparisons are executed within each level of the hierarchy (see Figure 5).

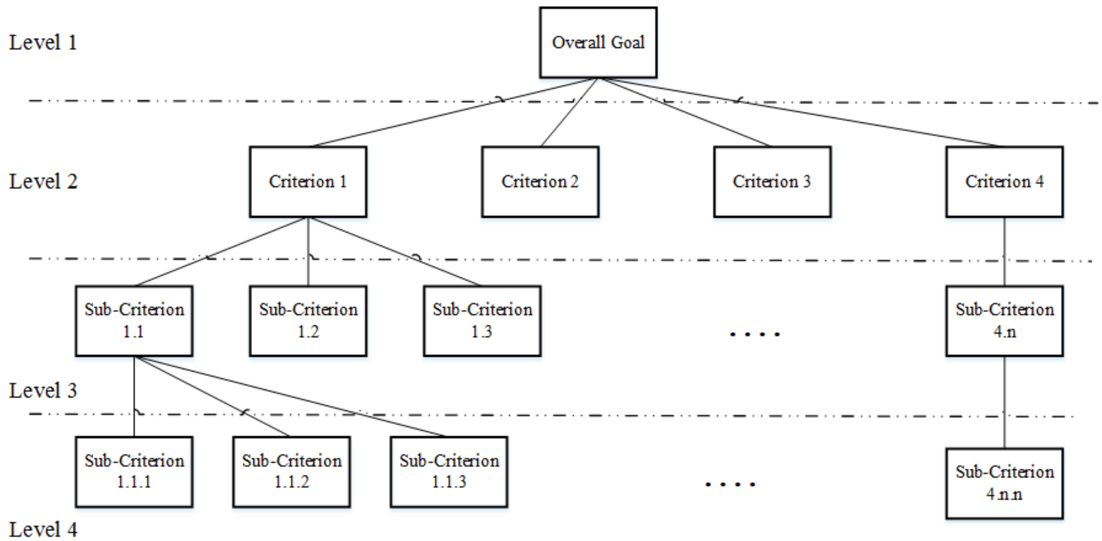


Figure 5: Decomposition of the problem into a hierarchy; *Absolute measurement*

Level 1 of the hierarchy is the goal and therefore it has the weight one. Level 2 of the hierarchy is composed of the criteria. Therefore the following is held on level 2, when $W_i$is the assigned weight to each criterion and i is the number of the criteria:

$$\sum_{i=1}^{n} W_i = 1 \tag{6}$$

In order to find the weights of the criteria on level 2, pair-wise comparisons should be executed and the *importance-value* of each comparison should be assigned based on Table 1. By having the *importance-values* from the pair-wise comparisons between all the criteria on level l, decision matrix D can be built (see Equation 7).

$$D = \begin{matrix} & \begin{matrix} C_1 & C_2 & C_3 & \cdots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} \end{matrix} \tag{7}$$

In Equation (7), the result of comparison C_i and C_j is assigned with an *importance-value* a_{ij} from Table 1and the value for comparison of C_j and C_i, a_{ji} is assigned with a reciprocal as follows:

$$a_{ji} = \frac{1}{a_{ij}} \tag{8}$$

Furthermore, the composed *D* matrix has to be normalized. To do this, each element is divided by:

$$S_j = \sum_{i=1}^{n} a_{ij} \tag{9}$$

An approximation of the priority vector[3] $(W_1 \dots W_n)$ can be computed by averaging each row [23]. Equation (9) and (10) present this approximation:

$$\begin{bmatrix} \frac{1}{S_1} & \frac{a_{12}}{S_2} & \frac{a_{13}}{S_3} & \cdots & \frac{a_{1n}}{S_n} \\ \frac{a_{21}}{S_1} & \frac{1}{S_2} & \frac{a_{23}}{S_3} & \cdots & \frac{a_{2n}}{S_n} \\ \frac{a_{31}}{S_1} & \frac{a_{32}}{S_2} & \frac{1}{S_3} & \cdots & \frac{a_{3n}}{S_n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{a_{n1}}{S_1} & \frac{a_{n2}}{S_2} & \frac{a_{n3}}{S_3} & \cdots & \frac{1}{S_n} \end{bmatrix} \xrightarrow{yields} \begin{matrix} K_1 = \frac{\sum_{j=1}^{n} a_{1j}}{n} \\ K_2 = \frac{\sum_{j=1}^{n} a_{2j}}{n} \\ \vdots \\ K_n = \frac{\sum_{j=1}^{n} a_{nj}}{n} \end{matrix} \tag{10}$$

The approximation of the Eigen-vector of the above matrix can be made as follows:

$$\widetilde{W} = \begin{bmatrix} \frac{K_1}{\sum_{i=1}^{n} K_i} \\ \frac{K_2}{\sum_{i=1}^{n} K_i} \\ \frac{K_3}{\sum_{i=1}^{n} K_i} \\ \vdots \\ \frac{K_n}{\sum_{i=1}^{n} K_i} \end{bmatrix} = \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \vdots \\ W_n \end{bmatrix} \tag{11}$$

Level 3 of the hierarchy is composed of the sub-criteria. On this level a new *D* matrix can be built for each criterion, with the same procedure as the level 1, and the weights can be assigned. When w_i is the assigned weight to each sub-criterion and *i* is the number of the sub-criteria, the following is held:

$$\sum_{i=1}^{n} w_i = W \tag{12}$$

Therefore, the sum of the weights of the sub-criteria on Level 3 has the same value as their corresponding criteria. For instance, on the hierarchy presented on Figure 5 the sum of the weights of sub-criteria, 1.1, 1.2, 1.3, has the same weight as criterion 1.

[3] Eigen-vector

By assigning all the weights, the analysis of the most important criteria and sub-criteria, for the overall goal, can be made.

2.3.2. Relative Measurement

In relative measurement paired comparisons are performed from the highest level to the lowest level in the hierarchy, which includes the alternatives level [22, 23] (see Figure 6). The lowest level in the hierarchy is the alternatives-level, which includes the alternatives for which a decision has to be made.

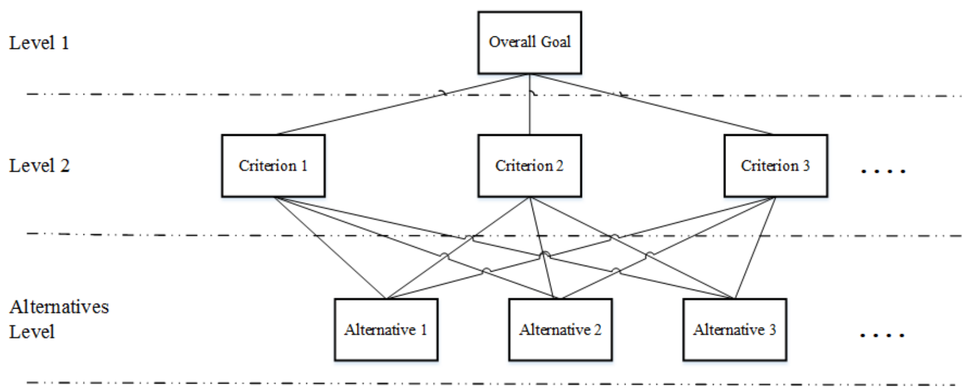


Figure 6: Decomposition of the problem into a hierarchy; *Relative measurement*

In this thesis, relative measurement and comparisons between alternatives will be used to decide between different sets of geo-spots (alternatives).

In order to perform relative measurement, firstly the weights of the criteria and sub-criteria (See Figure 6, Level 1 and Level 2) can be assigned following the same procedure as the absolute measurement. On the alternatives level a coupled matrix of alternatives and the criteria can be generated (see Equation 13). a_{ij} is the result of pair-wise comparisons to each criterion in alternative level which is based on the same rule (see table 1).

$$D = \begin{matrix} & C_1 & C_2 & C_3 & \cdots & C_n \\ Alt_1 \\ Alt_2 \\ Alt_3 \\ \vdots \\ Alt_n \end{matrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1m} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2m} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nm} \end{bmatrix} \quad (13)$$

In order to normalize the above matrix each criterion column should be adapted to the following equations. The choice depends on the nature of the criterion, if maximization is sought Equation (14.1) should be used and if minimization is required then Equation (14.2) is suitable.

$$\frac{(a_{ij})}{a_{ij}^{max}} \quad (14.1)$$

$$\frac{a_{ij}^{min}}{(a_{ij})} \quad (14.2)$$

By applying the above equations to the matrix D and deriving the normalized matrix D_n, the decision of the overall analysis can simply be calculated by multiplying D_n with the criteria weights ($\widetilde{W}$) on Level 2 [24].

$$D_n\widetilde{W} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix} \tag{15}$$

These d_i values are the basis for the decision making between the different alternatives. The alternative with the highest value of d_i can be selected as the best choice.

Table 1: The fundamental scale

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong impotence	An activity is strongly favored and this dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	$a_{ji} = \frac{1}{a_{ij}}$	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.
Rationals	Rations arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix.

Sources: [22, 23]

3. METHODOLOGY

In this chapter, the used methodology together with a detailed description of every step is presented. In addition, the criteria of geo-spot selection and the interview approach are presented. Lastly, the two sub-assemblies used in the case studies are described.

3.1. Project methodology

The project methodology shown in Figure 7 is inspired by Banks Simulation Methodology [25].

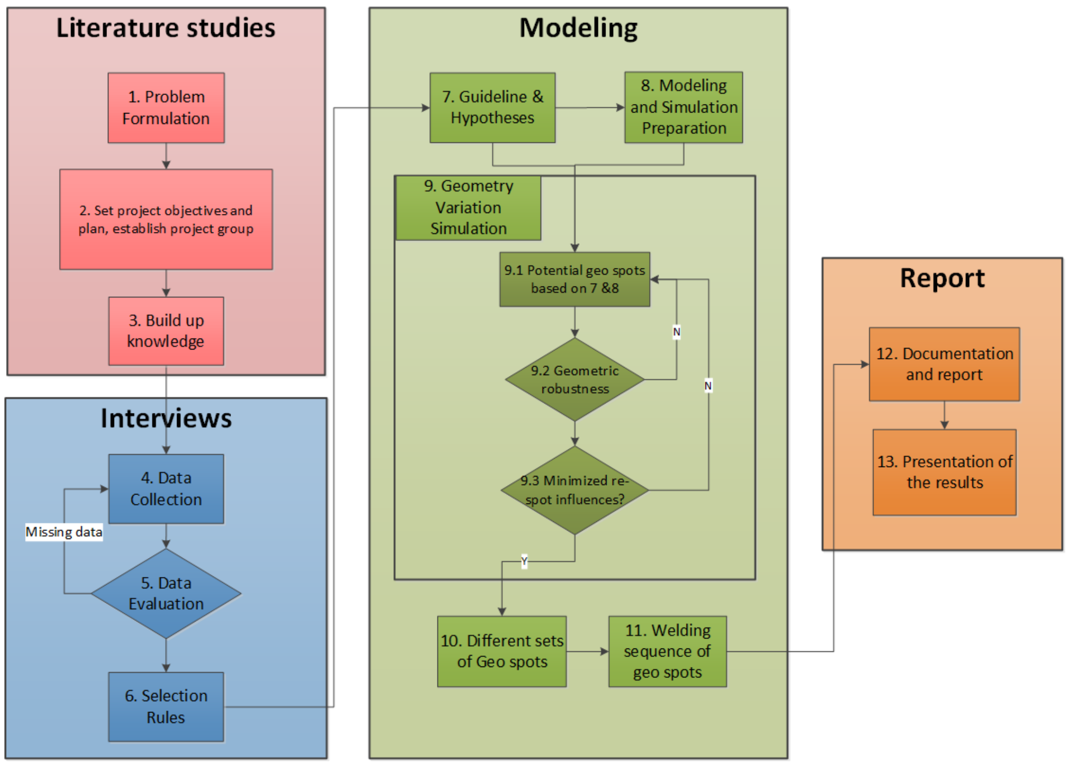


Figure 7: Project methodology inspired by Banks Simulation Methodology

The project methodology is divided into four main related areas, namely: literature studies, interviews, modeling and writing the report, which can be broken down to 13 steps as follows:

1- **Problem formulation.** The project attempts to tackle the problem of geometry assurance, which is an important task within automotive industry. The main task is to formulate a comprehensive work procedure for selection of geo-spots in non-rigid sheet metal assembly, which integrates industrial routines and simulation approaches.

2- **Set up project.** The main problem is broken down into several goals. These goals will be assigned into specific tasks in the project, which are the fundament of the project plan. This step also includes the establishment of the project group and coming up with a list of potential interviewees.

3- **Build up knowledge.** The project team builds up knowledge through literature reviews, modeling and simulation studies establishing contacts with experts within the area. In addition, the routines and solutions in industry are studied. There exists an industrial need to develop tools and methods to support the engineers in the task of selecting geo-spots. Currently, the task is still executed by engineers based on experience and skills rather than using computational support.

4- **Data collection.** Data are primarily collected through interviewing experts dealing with geometry assurance and the selection of geo-spots in the manufacturing engineering process. The interview questions are designed to acquire professional knowledge about selecting geo-spots. The project team establishes a list of general questions and hypotheses specifying different situations regarding the task of geo-spot selection. This approach is intended to reveal the knowledge on which the experts base their decisions. A detailed explanation of the interview approach can be found in Section 3.3.

5- **Data evaluation.** Data evaluation is conducted by accumulating all the collected data and applying the multi-criteria decision making method (AHP), described in detail in Section 2.3.

6- **Selection rules.** The selection rules are a set of hypotheses for selecting the geo-spots formulated before the interviews. These hypotheses are coupled to important identified factors affecting the geo-spot selection. The hypotheses are described in Section 4.1.2.

7- **Guideline.** This guideline for selecting geo-spots is a workflow, reflecting the industrial experience. The workflow consists of rules, verified contributing factors to the process of geo-spot selection and hypotheses verified during the interviews. Detailed description can be found in Section 4.2.3.

8- **Modeling and simulation preparation.** The simulation models are built using the CAT-tool RD&T. A simulation integrated workflow is proposed to support the decision process. Detailed description can be found in Section 5.1.

9- **Geometry variation simulation.** RD&T is used for conducting the variation simulation of the assembly process. This step is based on the following sub-steps:
   a. *Potential sets of geo-spots.* Following the guideline, different sets of geo-spots are proposed. This step is described in Section 5.4.1 and 5.4.4
   b. *Geometric robustness*. Variation simulation of the assembly is conducted for the generated sets of geo-spots. This step is described in Section 5.2.
   c. *Minimize the influence of respots.* The influence of respots on the assembly is investigated using the variation simulation function in RD&T. Detailed description can be found in Section 5.2.

10- **Finding a set of geo-spots.** By analyzing the simulation results in RD&T and utilizing the AHP method, the best set of the geo-spot is settled as the selected set. This step is described in Section 5.3.

11- **Welding sequence.** The sequence of the selected sets of geo-spots is tested and analyzed in RD&T. In this project, sequence analysis is based on the engineering experience and general rules derived from the interviews. The results achieved from the sequence analysis can be found in Appendix C.

12- **Documentation and report.** This step includes documenting the results and findings of the study.

13- **Presentation of the results.** The results achieved from the master thesis are presented in this step. The presentations can be categorized as academic and industrial presentations:

- *Master thesis defense*. Presenting the result for the academic advisors and defending the proposed methods and the results achieved.
- *Industrial Presentations.* Including mid-term and final presentations for the industrial advisors at the host company, VCC.

3.2. Criteria for selecting the geo-spots

In the *build up knowledge* step, it was identified that an appropriate set of geo-spots can improve the geometrical outcome of an assembly. In order to find appropriate sets of geo-spots the following criteria need to be considered:

Criterion 1: Assure geometry robustness and product functions

The assembly should be geometrically robust and the key features of the product should be assured. Therefore, the selection of geo-spots needs to serve these two purposes. The criterion is assigned to evaluate the geometrical outcome of the complete process, containing both geo-station and respot station. A particular simulation model is developed to verify the chosen geo-spots for this criterion (see Section 5.2, Model 3).

Criterion 2: Assure rigidity of parts to withstand forces

The rigidity of an assembly can be secured by selecting appropriate geo-spots. This means that the assembly should be stiff enough to withstand the applied forces from the subsequent processes. The criterion is used to evaluate the assembly after the geo-station. When the assembly is fetched by the robot's gripper, the geo-spots play an important role on assuring that the assembly can withstand the handling forces. To verify the rigidity of the assembly, a simulation model is designed to support the decision making (see Section 5.2, Model 3).

Criterion 3: Minimizing the influence of respots

The influence of the respots on the geometry should not be neglected and it is known to have a significant contribution to the deformations. The criterion is used to evaluate the assembly outcome after the respot station. A minimal influence from the respots on the assembly is sought. For analyzing the correlation between the selected geo-spots and the influence of respots, a simulation model is built and presented (see Section 5.2 Model 4).

3.3. Empirical data collection

In this section, the approach used in the interviews for collecting the required data is described in detail.

3.3.1. Interviewees

Selection of the geo-spots in industry is usually the result of cooperation between different departments. Some of the active participants in this process are manufacturing engineers, geometry engineers and design engineers. Therefore, the interviewees are selected from these different departments. The interviewees are selected in the following order based on their roles:

From Volvo Cars;

- *Car Body Design Department:* one engineer
- *Manufacturing Engineering Department*: seven engineers
- *Manufacturing Engineering Quality Geometry:* one engineer
- *Geometry Engineers from plant:* two engineers

From Volvo Trucks;

- *Geometry Engineers:* two engineers
- *Manufacturing Engineering BIW:* one engineer

3.3.2. General questions

The questionnaire generated for the interviews consists of nine open and general questions. These questions were divided into two sections. The first section of questions was designed specifically to refresh the interviewers' memory about the task of selecting geo-spots. After these questions, an assembly scenario is discussed during the interview. Then, the second section of the questions was asked to get detailed understanding of the factors affecting their decisions (see Appendix A.1).

3.3.3. Hypotheses and sketches

In order to generate some selection rules for geo-spots and to understand the decision making logic behind the choice of geo-spots, combinations of simple sketches and hypotheses were formulated before the interviews. These combinations were chosen based on the knowledge gained from literature studies etc. (The *Build up knowledge* step). In addition, through the *Build up knowledge* step, many common pitfalls in selection of geo-spots were identified. As an effort to depict these common pitfalls and challenges, a set of different sketches were put together. These sketches were coupled together with different hypotheses for selection of geo-spots which also derived from the initial discussions. By understanding the expert knowledge and their decisions on the sketches, the hypotheses could be verified. This result was thereafter used to generate the workflow presented in Section 4.2.3, modeling the experience at VCC and Volvo Trucks (see Appendix A.3).

3.3.4. Priority and evaluation table

A priority and evaluation table was designed to fulfill two tasks: (1) ranking the priorities of the *Classification Group (CG)* and the *Consideration Factors (CF)* within each *CG;* (2) finding the relation between each *CF* and its contribution to the three main criteria for geo-spot selection (see Figure 8 and see Appendix A.2).

The table lists 15 *CFs* derived from theory study (see Section 2.2.1) and initial discussions with the engineers. All the *CFs* were grouped into four different *CGs*, *Design concept (D)*, *Material properties (M)*, *Welding process parameters (WPP)* and *Welding process restrictions (WPR)*. *Design concept* is referred to the process strategy in geo-station and the design of parts. *Material properties* is referred to the characteristics of materials in the welding process of geo-spots. *WPP* and *WPR* are referring to the parameters and restrictions when it comes to geo-spot selection in this report.

The definitions of the *CF*s are as follows:

<u>CG1: Design concept</u>

CF1: Geometry specification – The definition of shape, dimensions and surface characteristics of a part.

CF2: Part thickness – The thickness of each part included in the sub-assembly.

CF3: Locating scheme – The positions of locators, clamps and supports in the sub-assembly process.

CF4: Type of part – e.g. bracket, reinforcement, console and panel.

CF5: Number of parts – The amount of parts in the sub-assembly process.

<u>CG2: Material properties</u>

CF6: Spring back effects – The effect caused by spring back after welding process.

CF7: Part stiffness – The rigidity of part resisting deformation caused by the process forces.

CF8: Material flow – The way that sheet metals move during the welding process.

<u>CG3: Welding process parameters</u>

CF9: The number of welding points – The number of welding points taken in the sub-assembly process, i.e. geo-spots and respots.

CF10: Welding sequence – The sequence of taking welding points in the sub-assembly process.

CF11: Welding force – The drag forces exerted by the welding guns during the sub-assembly process.

<u>CG4: Welding process restrictions</u>

CF12: The geometry of welding gun – The shape of the welding gun.

CF13: Loading and processing sequence (Sub-assembly sequence) – The sequence of loading parts to the sub-assembly.

CF14: Fixture orientation – The way the fixture is oriented in the sub-assembly cell.

CF15: Cycle time – The total time from the beginning to the end of the geo-spot welding process.

Task 1

Priority of elements
Opinions of the interviewees

Classification Groups (CG)	Priority of Group	Priority of Factors	Consideration factors (CF)	The relations between the selection criteria and consideration factors											
				Criterion 1				*Criterion 2*				*Criterion 3*			
				Assure geometry robustness				*Rigidity of parts withstand sub-assembly force*				*Low influence of respot points*			
Design concepts			Geometry specification	1	2	3	4	1	2	3	4	1	2	3	4
			Part thickness	1	2	3	4	1	2	3	4	1	2	3	4
			Locating scheme	1	2	3	4	1	2	3	4	1	2	3	4
			Type of part	1	2	3	4	1	2	3	4	1	2	3	4
			Number of parts	1	2	3	4	1	2	3	4	1	2	3	4
Material Properties			Spring back effects	1	2	3	4	1	2	3	4	1	2	3	4
			Part stiffness	1	2	3	4	1	2	3	4	1	2	3	4
			Material flow	1	2	3	4	1	2	3	4	1	2	3	4
Welding Process parameters			The amount of welding points	1	2	3	4	1	2	3	4	1	2	3	4
			Welding sequence	1	2	3	4	1	2	3	4	1	2	3	4
			Welding force	1	2	3	4	1	2	3	4	1	2	3	4
Welding Process restrictions			The geometry of welding gun	1	2	3	4	1	2	3	4	1	2	3	4
			Loading and processing sequence	1	2	3	4	1	2	3	4	1	2	3	4
			Fixture orientation	1	2	3	4	1	2	3	4	1	2	3	4
			Cycle time	1	2	3	4	1	2	3	4	1	2	3	4

Task 2

Root Cause Analysis
Relations assigned by the interviews

Figure 8: Priority and evaluation table

Task 1

The interviewees were asked to prioritize four *CGs* and each *CF* within each *CG*, respectively. The priority number should be given starting from 1 (the highest priority) (see Figure 8 and Appendix A.2). The result of priorities is presented in Section 4.1.3, Table 3.

Task 2

The relations (1 irrelevant, 2 weak relation, 3 intermediate relation, 4 strong relation) between the *CFs* and the main three criteria of geo-spot selection are assigned by the interviewees through choosing the number from 1 to 4 in each column corresponding to three criteria (see Figure 8 and see Appendix A.2). The result of the identified relations is presented in Section 4.1.3, Table 2.

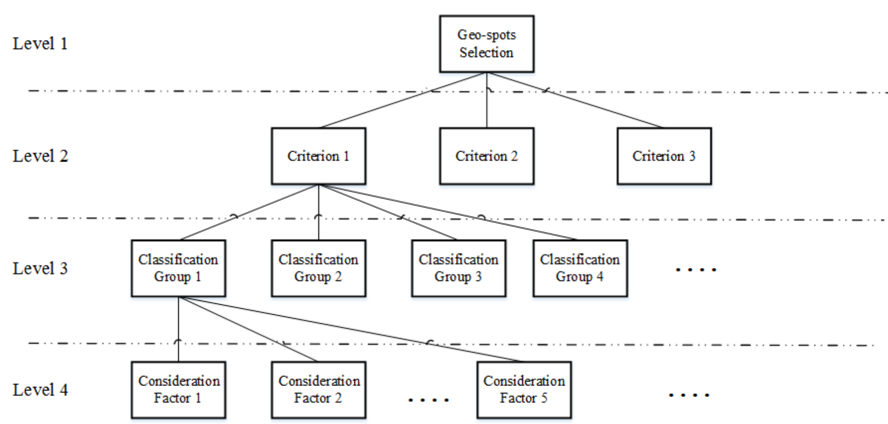


Figure 9: The hierarchy of AHP analysis in *Geo-spot Selection*

The construction of AHP analysis

The result of *Task 2* was analyzed in the Section 4.2.1, which constructed the hierarchy tree of *Root Cause Analysis* (see Figure 15). Based on the results of *Root Cause Analysis*, the constructed hierarchy can be used as the hierarchy of the AHP analysis in *Geo-spot selection* (see Figure 9).

The pair-wise comparisons of *CF* and *CG* in the AHP analysis in *Geo-spot selection* were based on the results from *Task 1*. The results about the priorities of groups and factors reflected the preferences of interviewees, which can be utilized as the input to the AHP analysis. Finally, the *importance-weights* of CGs and CFs and an overall priority list of CFs were summarized by the AHP analysis (Section 4.2.2).

3.4. Case study

Two sub-assemblies were chosen to be studied in the project. These industrial cases were used in the project for two purposes; for case discussion with the interviewees to identify their specific approaches of geo-spot selection and for simulation and verification purposes in RD&T software in order to test the proposed working procedure.

3.4.1. Case study models

Case A:

This sub-assembly consists of five parts, the base part (red) and three reinforcement pieces (yellow, blue and green) and one bracket assembly (green and grey) on the backside of the base part. In real assembly, the base and three reinforcements are located in the fixture. Later on, the bracket assembly is joined to the backside of the base part in another assembly step. There are some challenges related to this assembly:

1- What strategy is used for selecting geo-spots on the reinforcement parts to achieve the geometrical requirements of the base part?
2- How to handle process restrictions, such as the points that will be hidden due to sub-assembly sequences and the accessibility of the welding gun?
3- How to choose geo-spots to minimize the variation on the flanges of the base part?

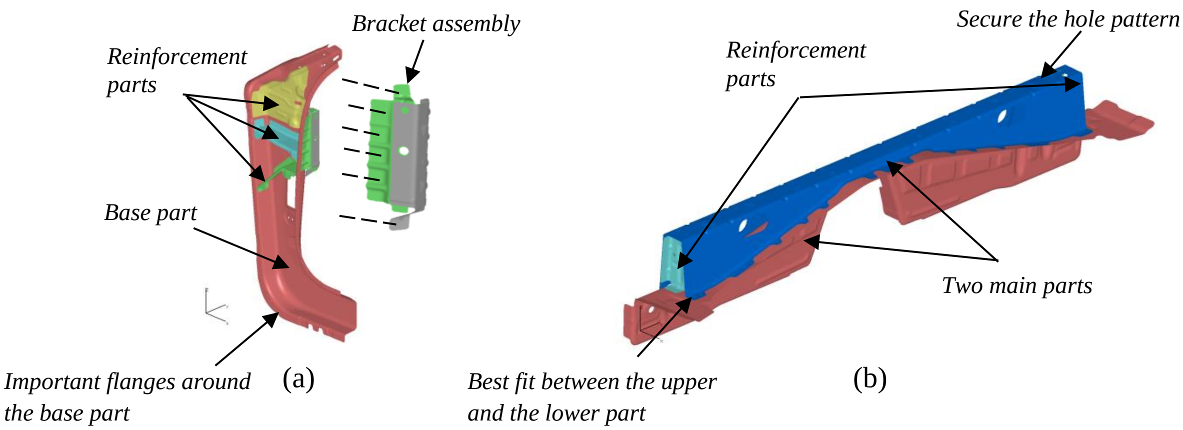


Figure 10: Case samples - (a) Case A, (b) Case B

Case B:

This sub-assembly consists of four pieces, two small reinforcement brackets on the side and two main parts (blue and red). In order to have a better welding accessibility, this part is assembled upside down. The blue part and the brackets are loaded into the fixture and later on the red part is assembled on top of them. The challenges related to this assembly are:

1- How to get the perfect fit between two main parts, when the locating schemes are restricted to one plane?
2- How to select the geometry points in order to handle the process limitations and to minimize the variation?

3.4.2. Case study scenario

In order to discuss the chosen cases under the same conditions with all the interviewees, a scenario was presented describing the conditions under which the parts are going to be assembled. This scenario will limit the discussion of geo-spot selection in the preassembly station (see Figure 11).

I. Basic information

Both sub-assemblies are planned to be produced in an automated production cell where the geo-spots are set while the parts are clamped in a fixture and the following respots are performed using a fixed gun. Figure 11 depicts an environment of the cell on which the discussions are based [26]:

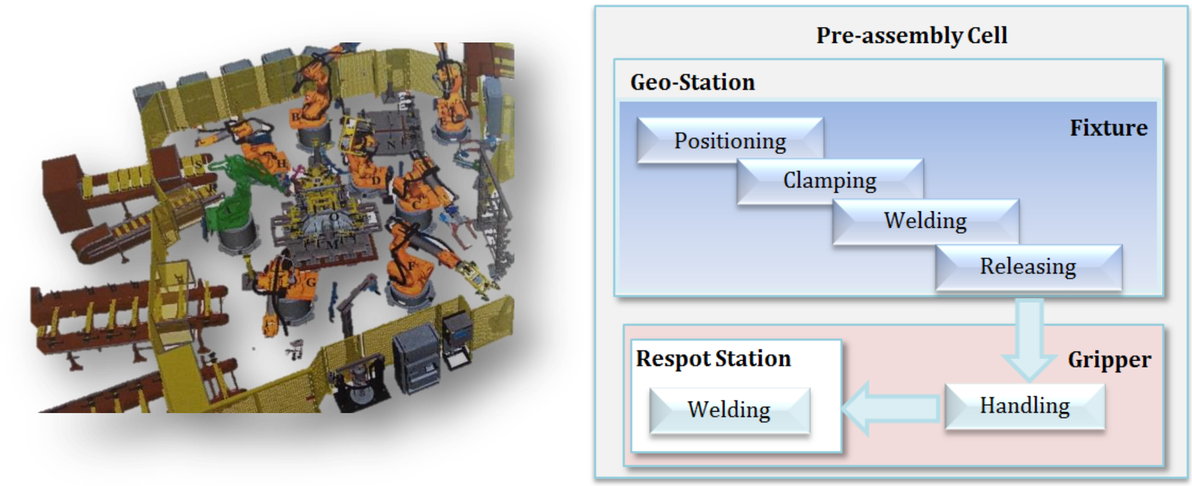


Figure 11: Production cell [26]

II. *Assemblies*

The part shapes are defined and the assembly sequence is known. Thus, the geometry of them can be visualized having a 3D CAD model. The locations of the welding points on the parts are defined. The geometrical requirements of the assemblies are specified.

III. *Assembly procedure*

1- Positioning

a. Parts are loaded by a gripper into the fixture. Therefore the deformation caused by the gripper, while it is holding the part, is taken into consideration.

2- Clamping

a. Parts are clamped simultaneously. The clamping sequence is not taken into consideration, because the deformation caused by clamping in a specific sequence is ignored.
b. The individual parts' locating schemes and the assemblies' locating schemes are defined. So, the position of the locators cannot be changed based on the interviewees' preference.
c. The geometry of the fixture is secured in advance. Tooling deviations are ignored. The clamps will force the locator surfaces to the nominal position.

3- Joining

a. The cycle time of welding process is known (e.g. 60 sec. for actual welding).
b. The amount of geo-spots welded in this cell is 12-15 points.
c. The reachability of the welding gun is perfect for each point. This means that all the defined welding points on the parts are accessible for the welding gun.
d. Choice of welding gun is ignored.
e. Only one spot weld is taken in each step. No interaction stemming from simultaneously taken spots are considered.

4- Release from fixture

a. The clamps are released simultaneously and spring back will occur.

5- Material handling

a. The sub-assembly is taken out from the fixture by a gripper. Therefore the deformation caused, while both fixture and gripper are holding the assembly, is taken into consideration.

6- Respot process

a. Respot points are welded by a fixed welding gun in the respot station, while the gripper is holding the sub-assembly. The assembly will be forced to a fixed position by the gun and deformation might occur.
b. Respot points should have minimum influence on the assembly's geometry. They aim for a situation where the respots can be welded in any sequences.

4. INTERVIEW RESULTS AND ANALYSIS

In this chapter, the gathered data from the interviews are presented. In addition, the analyzed data and the results derived from them are presented in the second part of this chapter.

4.1. Interview results

As mentioned in the methodology (Section 3.3), the interviews are divided into four different steps; general questions, case discussions, sketches and hypotheses and finally the priority and evaluation table. After gathering all interviewee's opinions about each step and summarizing them the following results were achieved.

4.1.1. Results from general and open questions

According to the interviews, the process of geo-spot selection is a time-consuming task, since it involves trial and error work with physical parts. Moreover, it is known to be complicated task, due to the multi-disciplinary nature of it. In this process many aspects need to be taken into consideration, thus having a standardized workflow for this process is required.

In order to achieve the best model for this purpose, the results from the questions have been classified in two different areas:

1) The general strategy for selection of geo-spots
2) Identifying the most important *Consideration Factors* (*CF*).

I. General strategy for selection of geo-spots

For initializing every task, a set of necessary data is required. For selection of geo-spots, the CAD models contain a lot of information that are necessary for selecting geo-spots, such as the shape of the product, locating schemes and geometry specifications. The engineers have to understand the functions of each part involved in the assembly, for instance important areas of the parts, the function of locators on parts, geometry specification, etc. However, that information is not sufficient to make a good decision.

Firstly, the engineers need to have a clear understanding of the results after the welding process; this is achieved by many years' experience of the welding process.

Secondly, the task requires the information about the assembly station such as *CF15* (Cycle time, limiting the number of welding spots allowed), *CF12* (The geometry of the welding gun, determining the accessibility of the gun) and *CF13* (Loading and processing sequence, determining the sequence of loading parts to the sub-assembly) (see Section 3.3.4). These are the pre-conditions which limit the choice of geo-spots and must be followed. After considering those pre-conditions a set of unavailable points for welding, so called "hidden points", will appear in the process. The hidden points are the points which are unavailable for welding since they belong to other assembly steps, or they have to be taken since they will be covered by some parts of the assembly. The understanding of how to filter out these points comes out from an iteration process between different departments including manufacturing and design. That is why in most of the cases manufacturing engineers are aware of the process limitation and the welding points needed to be taken initially. Nevertheless, to select suitable geo-spots, the focus should be only on the points which will secure the geometrical requirement. Last but not least, the lessons learned from previous projects can be additional support to the choice.

Different strategies are applied by the interviewees in the selection process due to different perceptions on how to tackle the problem. As an effort to unify those different strategies the following order is proposed:

- Identify the important mating surfaces of the sub-assembly by looking around the model and thinking about the influence of the parts on the sub-assembly
- Lock the geometry by selecting the geo-spots avoiding the instable areas of the assembly.
- Foresee the outcome of welding process by experience and think about geometry demands and the geometry of parts when released from fixture.
- Choose the points in accordance with earlier projects and similar parts.

After the initial set of geo-spots is selected, the outcome of them is analyzed in a subsequent process, in which physical measurements and physical trial and error are executed. This process, which is also referred to as physical matching and trimming, can be summarized as follows:

1. Measure and adjust fixture to nominal position
2. Ingoing parts should be measured before physical matching and trimming
3. Place the parts in the fixture
4. Close the clamps in the right sequence and study the effects on the clamped parts
5. Measure the parts to identify part deformation caused by clamping
6. Mate the parts and resolve conflicts between mating surfaces
7. Close the gaps with geo-spots
8. Set the respots and check the outcome

Moreover the data base, CM4D (Coordinate Measurement Machine Management Mechanism for Data) is used to record the measurement data. By looking through the measurement diagrams, part specifications can be checked.

II. Identifying important Consideration Factors (CFs)

During the selection of the geo-spots different aspects should be taken into consideration, either simultaneously or in a logical order. The factors considered to be the most important ones, mentioned by the majority of the interviewees were:

1. The known deviation of the parts
2. The function of the part
3. The stiffness of the assembly
4. The type of equipment used in the welding process: welding gun and fixture
5. The thicknesses of the parts
6. How to minimize the spring back effect
7. The locating schemes

There are additional *CFs* that need to be concerned. Firstly, while *CF10* (Welding sequence) seems to have a great impact on the selection process, but according to the interviewees' opinions, the sequence is not considered so often when it only comes to the task of selecting the geo-spots. The most important influence of welding sequence will show off after selection of the geo-spots, examining the resulting gaps and twists in the assembly.

Some other "known to be" important *CF* is the effect of drag forces[4] on the parts. Even though *CF11* (Welding force) and its effect on the part geometry cannot be neglected, it does not influence the selection process at all. Another process factor is the energy required for spot welding. As it was mentioned in Section 2.2, using more thermal resistant materials or usage of more electrical current and increasing the time of the welding will produce more heat energy and might result in getting deformed geometries. However in this project the heat influence is neglected (see Section 1.6).

CF9 (The amount of welding spots) is another factor that can determine the rigidity of parts. It is desired to have as many as possible spots in the pre-assembly cell, but the number of spots is limited by the *CF15* (Cycle time) in the station. Therefore, there are always a limited number of points that could be set in the geo-station. The general rule for determining the amount of geo-spots is to have at least three points on the main plane of the part to lock the main axis. If applicable, these points are often selected in a way to form the largest triangle on planes. This rule is also dependent on the size and stiffness of the parts, the bigger, softer and more complex the parts are, the more points are needed to lock the geometry.

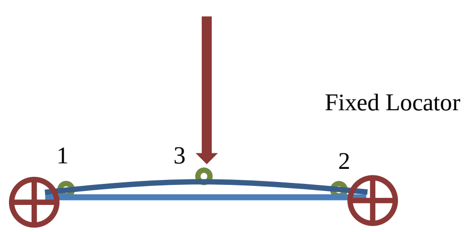
4.1.2. Results from sketches

In order to make a logical connection between the identified *CFs* and some common pitfalls and issues in geo-spot selection a set of hypotheses and sketches were presented and analyzed during the interviews.

Sketch 1: Hypothesis 1

One of the most common approaches towards geo-spot selection is to choose the geo-spots with respect to the locating system. Therefore, the hypothesis to cover this approach is described as:

H1. The welding points that are close to locators should be chosen primarily as geo spots.



Sketch 1: Hypotheses1; choosing the geo-spots close to locators

As it can be seen in Sketch 1, there are two locators at the near edge of the two mating surfaces. The existing gap between the mated planes is the result of the fabrication error in the parts. There are three available welding points on this sketch which are numbered from 1 to 3.

To start with the selection process, geometrical requirement should be checked in advance, checking whether the assembly allows having such gaps or not. If the geometry requires the assembly to be without any gaps, the middle point will be selected initially to reduce the gap size as much as possible.

[4] Drag force is the force exerted by the welding gun which will drag the sheet metal during the process.

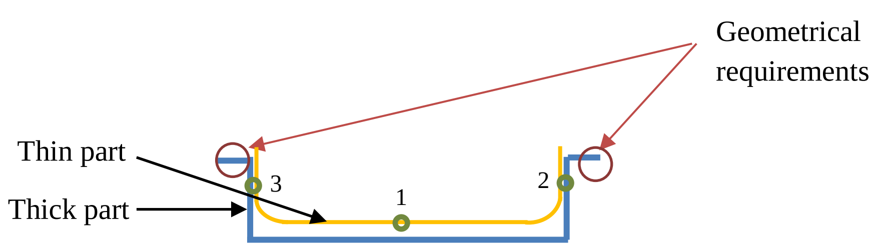
If geometrical requirement allows having such gaps, then most of engineers agreed upon starting by choosing the geo-spots close to the locators. Apart from geometrical requirement, there are two other issues that should be concerned, the material thickness and the distance between two fixed locators. In order to assure the welding quality, the thicknesses of the parts must be taken into consideration. Material thickness also determines the welding gun forces required for closing the gap. Moreover, if the distance between the locators is too short, then welding the points close to the locators will produce a gap in the middle which is harder to close.

Sketch 2: Hypothesis 2

The other important factor, as mentioned before, is to assure the geometrical requirements. Often when thinking about the sequence of the welding points, geometrical requirement will decide the most important points to be welded firstly. Sometimes additional points are needed to assure these requirements. The second hypothesis handles these requirements:

H2. The welding points that determine the geometrical requirement of part should be taken as geo spots.

Now considering the following sketch, this hypothesis could be elaborated more.



Sketch 2: Hypothesis 2; geo-spots should determine geometric requirement

By looking at the requirements and shape of the assembly in Sketch 2, it can be realized that the locating scheme should firstly secure that the bottom surfaces will attach together. Thus, the best option is to have a clamp on the bottom (near WP1) to close the gap. If there is no such option, the clamps should be placed somewhere near the important geometry areas (near WP2 and WP3) that are assigned to the geometrical requirements. Secondly, material thickness and stiffness should be checked. In this case, the thin part is loaded into the thick base part. There are three welding points spread over the bottom area and two sides of the thin part.

The most common welding sequence in this case, is to start from the point (WP1) on the bottom to close the biggest gap and then two sides. For choosing this sequence, the inner flanges should have the ability to bend after welding the middle point.

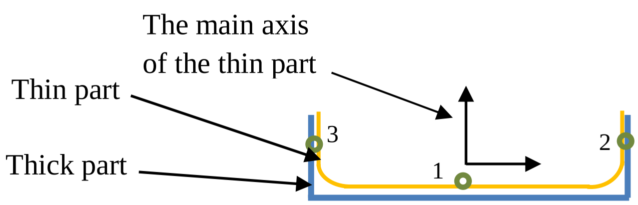
The other possible option is to start welding from one side (e.g. WP2), then bottom (WP1), and lastly weld the point (e.g. WP3) on the other side. This approach will cause a bigger gap on the final flange and distort the whole assembly.

The last sequence is starting to weld from the both sides (e.g. firstly weld WP2 and secondly weld WP3) and then the bottom point (WP1). In this sequence after welding the both sides, closing the bottom gap will cause big deformations on the flanges. Therefore, the requirements cannot be secured by this sequence.

Sketch 3: Hypothesis 3

Now, if we consider a case when there is no requirement on the parts, then the most important aspect to think about is to lock the main axis of the part (see Sketch 3). Therefore, the next hypothesis can be defined as:

H3. The welding points that contribute to lock the main axis of the surface should be considered as geo spots



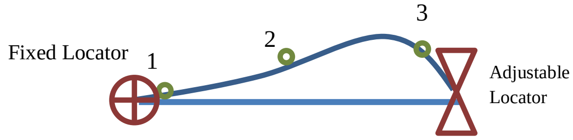
Sketch 3: Hypothesis 3; geo-spots should lock the main axis

In this case although most of the interviewees agreed that the sequence of welding is not important at all, but they preferred to lock the main axis of the thin part, which is on the bottom surface of the thin part, to get the best welding outcome. Thicknesses still need to be checked to foresee the outcome of the welding in this case.

Sketch 4: Hypothesis 4

As it was discussed on the first sketch, to avoid the built-in gap between the parts, the locating scheme can be adjusted to allow material flow [5]during welding.

H4. The welding points that contribute most to the material flow should be selected as geo-spots



Sketch 4: Hypothesis 4; geo-spots for controlling the material flow

In Sketch 4, there is one locator at the one end of part (Fixed locator) and one clamp on the other edge (Adjustable locator[6]). By reducing the clamp force of the adjustable locator, the material can glide underneath the clamp while welding. Therefore, the gap which is caused by the fabrication error could be handled.

[5] In this project, material flow is referred to the way sheet metals move during the welding process
[6] Adjustable locator in this report is referred to a locator which allows the material glide during the welding process

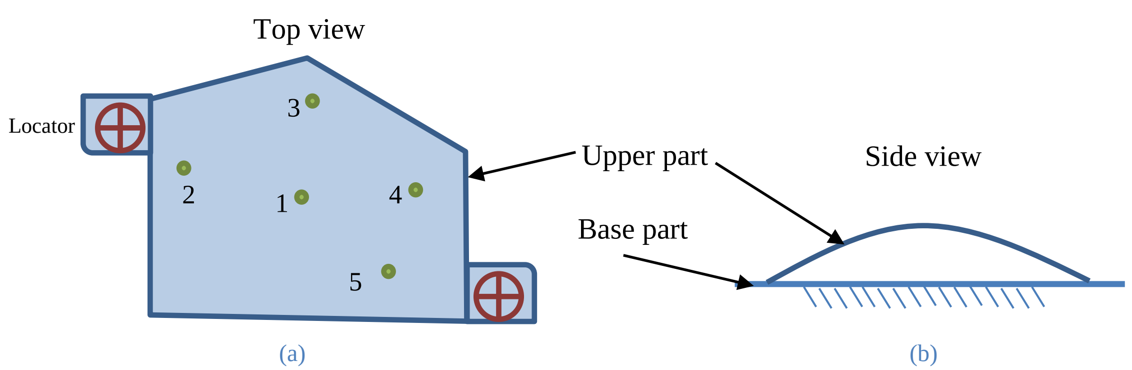
In this approach, the welding sequence is of importance to control the material flow. The most common sequence for this purpose is to firstly choose WP2, since it has the biggest effect on material flow. Although WP1 is near the fixed locator, it is not necessary to be chosen as a geo-spot, since it gives a small contribution to material flow. This case looks simple in a 2D sketch.

However, if this case changes to 3D, the situation will get more complicated. This time, the selection might be changed into starting with WP1 to WP3 to assure that the material is flowing in the right direction. In addition, even if the material could glide under adjustable locator, it is hard to predict the behavior of material flow. (In 3D view, the upper sheet might glide either towards the center or left and right side.) Thus, having a good solution for the adjusted locator which will let the sheets glide or designing very long slot hole to guide the material flow should be considered carefully in these situations.

Sketch 5: Hypothesis 5

In Sketch 5, the top view and the side view of the parts are shown. In this case, the locating system is restricted only to the small flanges on the both sides of the two matched sheets. The challenge here is to make a trade of between choosing the points close to the locators or lock the main axis of the part to get rid of the gap in the middle. Therefore, the next hypothesis is defined as;

H5. The geo-spots should be selected as spread as possible to act as a part to part locating system, when the clamping system cannot be placed in an optimal position (due to process restrictions).



Sketch 5: Hypothesis 5; geo-spots acting as locating system (a): top view (b): side view

The main strategy in this case is to spread the points as much as possible to get the biggest triangle on the plane. This strategy comes from the general rule behind the selection of the locating points (3-2-1 system). Regardless of the gap between parts, there was a common agreement among all interviewees to select two points close to the locators (WP5 and WP2) and the point lying on the top of the part (WP3).

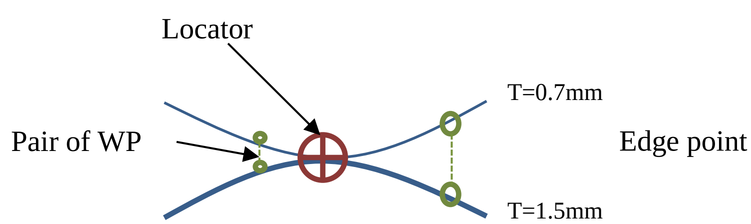
If there is a gap in the middle (see the side view), then the part thickness and stiffness should be taken into consideration. If the material is stiff enough then by selecting the middle point (WP1) the whole upper surface will be forced to follow the geometry of the base part. On the other hand, if the part is not stiff, then the problem of having bulbs will occur. Thus, the selection of the middle point is ruled out.

Another possible strategy is to let the plates glide at one locating position by changing one of the locators to a slot hole or a clamp with gliding ability. After getting the parts following each other, then the welding points near the locators can be selected as geo-spots to fix the position of the parts.

Sketch 6: Hypothesis 6

Sketch 6 is designed to discuss about the influence of material thickness on the selection of geo-spots. Looking at the parts curvatures and thicknesses (0.7 mm and 1.5 mm), it can be inferred that the thick part (stiff part) has a stronger influence than the thin part (non-stiff) on the geometry outcome. Thus, knowing the part that determines the geometrical requirement is important. The next hypothesis that was set for this purpose is:

> **H6. The selection of geo-spots should consider material thickness due to the fact that a stiffer part has more influence on the geometry compared to a less stiff part.**



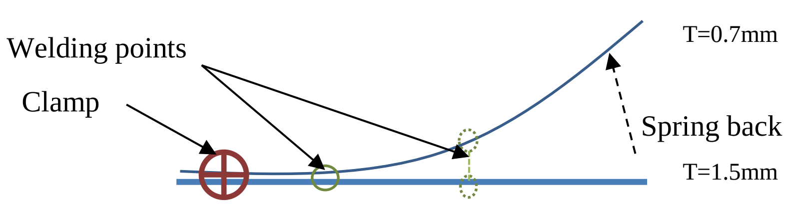
Sketch 6: Hypothesis 6; geo-spots determining the geometry of the most important part

If the thick ($T = 1.5\ mm$) part is stiffer than the thin ($T = 0.7mm$) part, selecting the WP near the locator and later locking the edge points makes the assembly follow the geometry of the thick part. Generally, the reinforcement parts (e.g. thick part) are thicker than the function parts (e.g. thin part). However, the geometrical requirement is assigned to the function part. In the case of Sketch 6, even if the thin part is more important, it is impossible to reshape the thick part to follow the geometry of thin part, since the thick part is formed in the opposite direction. In this situation, the geometry of the thick part has to be corrected before starting the welding process.

Sketch 7: Hypothesis 7

One of the main aspects to think about while selecting geo-spots is the geometry outcome after welding of each point. The spring back effect is a non-neglected factor when considering the selection of geo-spots. In order to describe this aspect more, the following sketch was discussed with the interviewees.

> **H7. The welding points reducing the spring back effect should be selected as geo points.**



Sketch 7: Hypothesis 7; select geo-spots to reduce spring back effect

In this situation, both of the welding points are required for reducing the spring back effect. However, if there is a trade of between selecting only one of those points, the effect after releasing the assembly from the clamp should be considered. Selecting the welding point near the clamp will not contribute to close the gap between parts, still it is better for securing the position and less spring back is expected after releasing the clamp. On the other hand, selecting the welding point far from the clamp will force the thin part to follow the geometry of the thick part but more spring back is expected in the clamped area when the clamp is released.

4.1.3. Results from priority and evaluation table

In Table 2 fifteen *CFs* of welding process in non-rigid sheet metal assembly are listed and categorized into four *CGs*. Table 2 presents an overview of all interviewees' opinions about the relations between *CFs* and the three main criteria of selecting geo-spots. The strength of relation is partitioned into four levels: *irrelevant (Ir.), weak (W), intermediate (M)* and *strong (S)*. The numbers in the table indicates the number of interviewee agreed with the specific relation strength.

Table 2: The relation between the selection criteria and consideration factors

Classification Groups (CGs)	**Consideration Factors (CFs)**	**The relation between the selection criteria and consideration factors**											
		Criterion 1[7]				*Criterion 2*[8]				*Criterion 3*[9]			
		Assure geometry robustness				*Rigidity of assembly*				*Low influence of respot points*			
Design concepts	Geometry specification	1	1	5	7	1	2	3	8	2	6	4	2
	Part thickness	1	4	9	0	0	1	12	1	2	4	8	0
	Locating scheme	0	1	2	11	1	0	3	10	6	3	4	1
	Type of part	1	2	9	2	1	5	2	6	5	7	0	2
	Number of parts	5	6	3	0	6	4	4	0	9	4	1	0
Material Properties	Spring back effect	0	2	7	5	1	2	7	4	2	4	7	1
	Part stiffness	1	2	7	4	0	1	4	9	2	5	5	2
	Material flow	0	11	3	0	3	5	4	2	5	6	3	0
WPP	The amount of WP	1	2	6	5	0	0	6	8	4	4	2	4
	Welding sequence	0	2	10	2	1	1	6	6	3	5	5	1
	Welding force	3	6	4	1	4	7	1	2	5	3	5	1
WPR	The geometry of welding gun	5	7	2	0	6	4	2	2	9	5	0	0
	Loading and processing sequence	0	7	5	2	1	3	7	3	7	4	3	0
	Fixture orientation	4	7	1	2	3	7	3	1	9	3	1	1
	Cycle time	4	3	4	3	2	2	6	4	8	1	3	2
The relation scale:		**Ir.**	**W**	**M**	**S**	**Ir.**	**W**	**M**	**S**	**Ir.**	**W**	**M**	**S**

In *Criterion 1* (Assure geometry robustness), almost all interviewees agreed that *CF3* (Locating schemes) has a strong relation to the *Criterion 1*. There are only few *CFs* considered as *irrelevant (Ir.)*. This is

[7] Defined in Section 3.2, Criterion 1
[8] Defined in Section 3.2, Criterion 2
[9] Defined in Section 3.2, Criterion 3

because there are synergies among all factors and they should be considered together in order to assure robustness.

In *Criterion 2* (Rigidity of assembly), main *CFs* are: *CF1* (Geometry specification), *CF2* (Locating scheme), *CF3* (Type of part), *CF7* (Part stiffness), *CF9* (The amount of welding points) and *CF10* (Welding sequence). Six interviewees agreed that *CF5* (Number of parts) and *CF12* (The geometry of welding gun) are irrelevant to the *Criterion 2*. Additionally, many interviewees mentioned that the intermediate *CFs* (e.g. Part thickness, Spring back effect, Loading and processing sequence and Fixture orientation) could have potential strong influence on the outcome and should be considered carefully. *CF15* (Cycle time) does not directly influence the *Criterion 2*, while it determines *CF9* (The amount of welding points) in the geo-station that has strong influence on it.

In *Criterion 3* (Low influence of respots), most of interviewees agreed that no *CFs* significantly contribute to minimize the influence of respots. In other words, if the geometry of parts can be assured at the geo-station, respots can be freely welded. In addition, *CG4* (WPR) was regarded as irrelevant to the criterion.

Table 3 describes the *Priority of Group* and the *Priority of Factor* within each *CGs* (see section 3.3.4). It shows the priority of *CFs* and *CGs* while selecting geo-spots. The most important factors are ranked from number 1, to the least important, number 4. The data was collected from *manufacturing engineers* (M), *design engineers* (D), *factory engineers* (F) and *manufacturing engineering managers* (C).

The opinions of the interviewees are diverse due to their different work responsibilities, which significantly affects their decisions. The engineers from manufacturing department think that *CG2* (Material properties) have the second rank in the *Priority of Groups*. By contrast, the engineers from the factory and the managers prefer to consider *CG3* (WPP) or *CG4* (WPR) at the second place of priority, because these factors belong to their work responsibilities. What makes the managers' (C) opinions rather different might be the fact that they need to consider the cost of equipment and cycle time of the process.

On the other hand, there are still some common characteristics in their priorities. *CG1* (Design concepts) is known as the most important *CG* influencing on the selection of geo-spots. In the *CG1* (Design concepts), the three highest *CFs* are *CF1* (Geometry specification), *CF3* (Locating scheme) and *CF4* (Type of part). In the *CG2* (Material properties), *CF7* (Part stiffness) has the highest priority to select geo-spots, which means that it is crucial that the parts welded by geo-spots should withstand the force of respot welding process. In the *CG3* (WPP), *CF10* (Welding sequence) has higher priority than other two *CFs*, which has more impact on the geometry of assembly. In addition, *CF11* (Welding force) is not considered by most of interviewees when it comes to selection of geo-spots. Lastly, in the *CG4* (WPR), there is no obvious pattern in the priority of the *CFs* due to fact that all those factors should be considered at the same time.

Table 3: The priority of factors

Classification Groups (CGs)	**Priority of Group**														**Priority of Factor**														**Consideration Factors (CFs)**
Design Concepts	1	1	1	1	1	1	1	1	1	1	3	1	2	4	3	1	1	1	3	2	2	2	2	3	1	2	1	4	Geometry specification
															4	4	3	4	5	3	5	5	4	4	4	3	3	2	Part thickness
															2	2	2	2	4	4	1	3	3	2	3	1	1	5	Locating scheme
															1	3	3	3	1	1	3	1	1	1	2	4	2	1	Type of part
															5	5	3	5	2	5	4	4	5	5	5	5	4	3	Number of parts
Material Properties	2	2	4	3	4	2	4	2	2	4	4	3	2	1	2	2	1	2	2	2	2	3	2	2	2	1	1	3	Spring back effect
															1	1	3	3	1	3	1	2	1	1	1	2	1	2	Part stiffness
															3	3	2	1	3	1	3	1	3	3	3	3	3	1	Material flow
WPP	3	4	2	2	3	2	2	4	3	3	2	2	2	3	1	2	1	1	2	2	2	2	2	3	1	1	2	3	The amount of WP
															2	1	2	2	1	1	1	1	1	1	3	2	1	2	Welding sequence
															3	3	3	3	3	3	3	3	3	2	2	3	1	1	Welding force
WPR	4	2	3	4	2	4	3	3	4	2	1	4	2	2	4	1	4	4	4	3	2	2	3	2	3	2	3	1	The geometry of Welding gun
															4	4	2	2	2	4	1	1	1	3	2	1	2	4	Loading and processing sequence
															4	3	2	1	3	1	3	4	4	4	4	4	2	2	Fixture orientation
															4	2	1	3	1	2	4	3	2	1	1	3	2	3	Cycle time
Departments	M	M	D	F	C	C	F	M	M	M	M	M	M	M	M	M	D	F	C	C	F	M	M	M	M	M	M	M	

Table above provides an overview of the interviewees' opinions, about the importance of each classification and factor in geo-spot selection. The importance of the elements are weighed from 1 (most important) to 4 (least important).

4.1.4. Case discussions

For a deeper understanding of the way of thinking behind geo-spots selection two industrial cases were discussed together with the interviewees, see Figure 12.

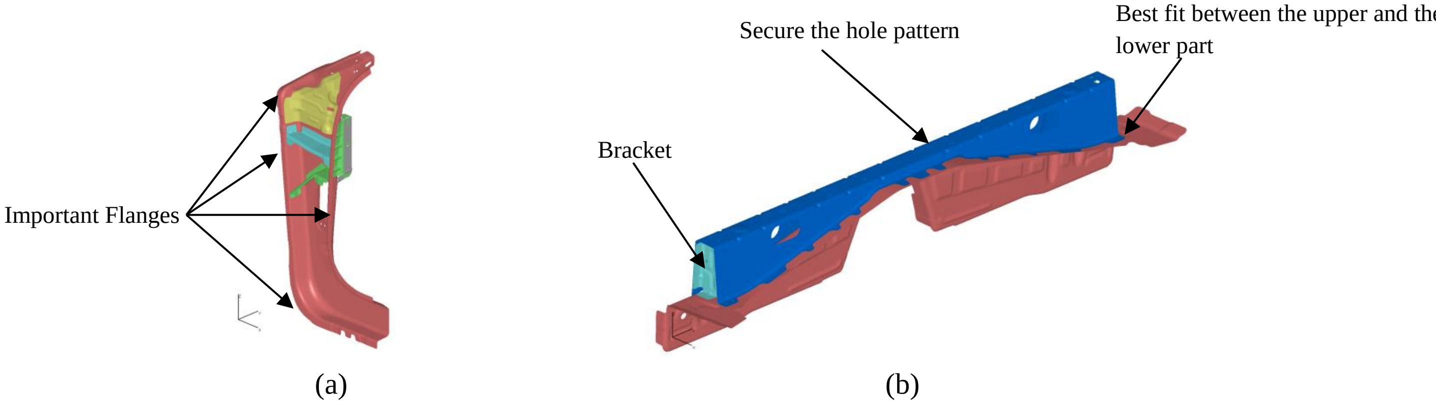


Figure 12: Case samples - (a) Case A, (b) Case B

Case A

Step 1: Understand the functions of each part in the assembly

The most important geometrical requirements set on the assembly are on the red part (base part) having the important flanges around the part (see Figure 12). The yellow, blue and green parts welded on the base part are only reinforcement parts and the geometrical requirements set on them in the assembly are not as important as the requirements on the base part. The "*bracket assembly*" (see Figure 13) was not discussed assuming that that the corresponding welding points on this part will be set last.

Step 2: Check the positions of all locators: the whole sub-assembly, the locators on each part

One of the challenges in the geo-spot selection of case A is on the left side of the yellow reinforcement. In case of the existence of a gap between the base part and yellow part, setting one of the welding points WP1, WP2 and WP3 will cause deformation on the important flange in that area, see Figure 13. Therefore, it is better to make sure that the red part and the yellow part are attached together by the locators.

There should be at least one available WP on the bottom flange of blue part. The WP4 on the bottom flange of the blue part (see Figure 13) joins three parts together, the base part, the blue part and the *bracket assembly*. So, this WP cannot be set before welding the *bracket assembly*. Since there is no WP available on this flange, the engineer should discuss with the designer to change the design or add a clamp to secure that the blue part is attached to the bottom (see Section 4.1.2, Sketch 2: Hypothesis 2).

Step3: Selection of the geo-spots

a) Yellow part

The most common candidates for geo-spots on this part are WP5, WP6 and WP7 (see Figure 13). These points will lock the position of two parts (base and yellow parts) and make the yellow part follow the geometry of the base part (see Section 4.1.2, Sketch 2: Hypothesis 2). The geo-spots on this part should be selected near the locators (see Section 4.1.2, Sketch 1: Hypothesis 1 and Sketch 5: Hypothesis 5). The prerequisite of these choices are that the locating scheme can assure the two parts attach closely in the mating surfaces and the welding points there will not distort both parts.

b) Blue part

The loading sequence restricts the availability of WP8 and WP9 (see Figure 13), since this point will be hidden after the assembly of the *bracket assembly*. Therefore, this point should be taken as a geo-spot. It is also important to lock the Y direction for this part before setting the WP10, WP11, WP12, WP13, WP14 and WP15 (see Figure 13, c) (see Section 4.1.2, Sketch 2: Hypothesis 2). WP8 lies on the 45 degree flange and contributes somewhat to lock the part in Y direction. However, this is not the best first choice.

As it was discussed while checking the location scheme, putting a geo-spot on the bottom flange to push the part to the bottom and follow the geometry of the base part is the favorable decision on this part. Since there are no points on the bottom flange, due to the assembly limitations, the design of this reinforcement or the clamping positions should be reconsidered (see Section 4.1.2, Sketch 2: Hypothesis 2)

Another suggestion is to pick WP10 and WP14, since there are *bird-beaks* (small reinforcements) on the flanges on which those points are located on. Thus, those two WPs should be selected as geo-spots and then the welding point in the middle is needed to bend the bottom flange.

c) Green part

WP16 and WP17 are available on the bottom flanges (see Figure 13, d). The Geo-spots should be selected on the bottom flanges at first (see Section 4.1.2, Sketch 2: Hypothesis 2). WP11 and WP15 are two WPs on the side flanges. The right side flange seems to be stiffer, due to existence of a *bird-beak*, while the left flange seems flimsy and limber. Therefore the WP11 should be welded first, while taking the sequence into consideration (See Section 4.1.2, Sketch 6: Hypothesis 6). It is also suggested to take an extra point on the biggest flange in the bottom, which should be on the left side of it to secure that the green part will follow the geometry of the base part.

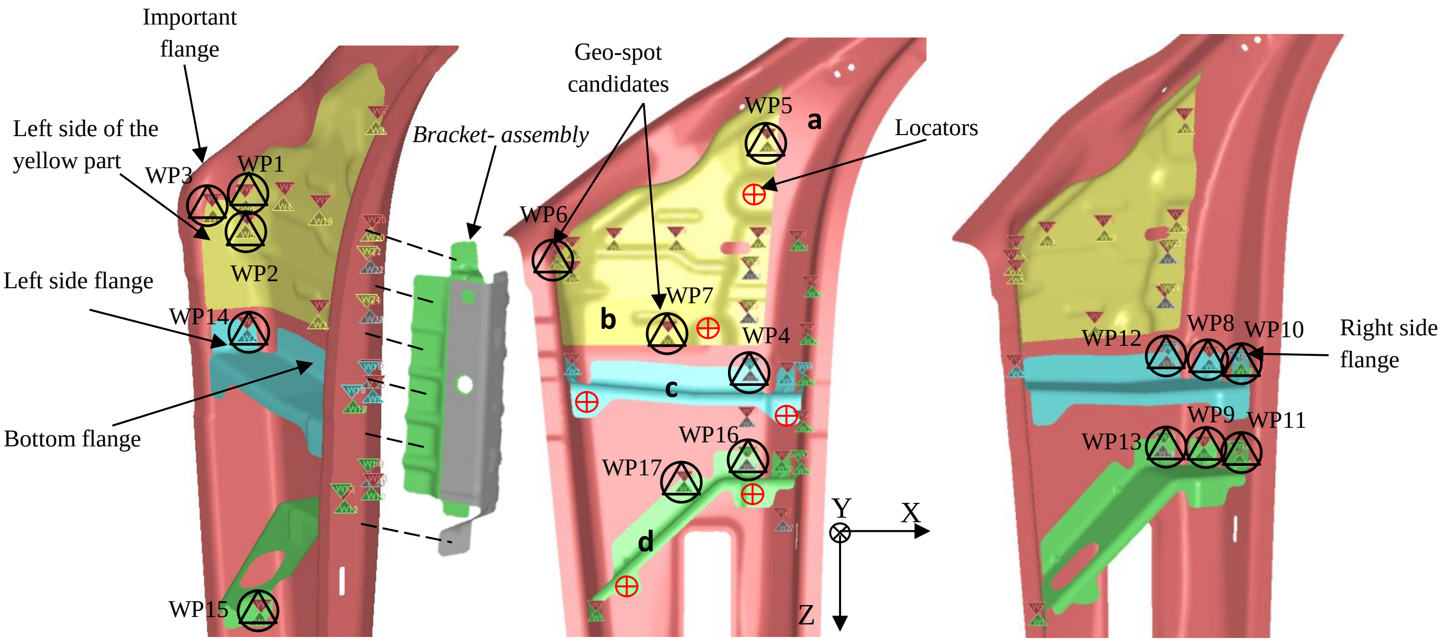


Figure 13: Geo-spot selection on Case A

(a) Red part (b) Yellow part (c) Blue part (d) Green part

Case B

Step1: Understand the functions of each part in the assembly

The most important requirement for Case B is the accuracy of the flanges Z direction and the hole pattern in it, which influences the assembly of the other parts later on. The flanges on the red part are also of importance in terms of geometry since they might collide with latter assemblies. The two small brackets on the both sides are reinforcement. The geometries of the two small brackets are not considered as critical in the final assembly (see Figure 14).

Step2: Check the positions of all locators: the whole sub-assembly, the locators on each part

In production this assembly is welded upside down. This means that the blue part is first located in the fixture and then two brackets are welded on both sides initially. Later on, the red part is welded on top of them.

Locking the Z direction is the main priority of the locating scheme in this case. There are no welding points placed near the locators.

Step3: Selection of the geo-spots

Basically, the suitable strategy of selecting the geo-spots is to distribute them evenly on the Z and X flanges. In Case B, the sequence of welding geo-spots is more important to secure the geometry outcome. Interviewees had two general approaches to assure the geometry outcome. These two approaches come from different perceptions of the important functions of the part.

a. The welding points on the Z flange should be fixed firstly, because the clamps and locators secure the part in Z direction (WP1-WP6). This way on the Part (a) the flange in X direction has the possibility to adjust following the geometry Part (b).
b. The welding points on the X plane should be taken first (WP7-WP12). This approach comes from the fact that the X plane is reinforced with the ridges, and also the Z flange on part (a) is split in several “*ears*” and looks flimsy.

The welding sequence has two general strategies described by interviewees: (1) to start welding on one flange from middle to both sides; (2) to start welding on one flange from one edge to the other end. Therefore, four different combination sets of points that can be generated when taking the welding sequence in mind:

a.1) Start with the Z flange and lock the middle points first and approach to both sides. Then the sequence is: (WP4, WP3, WP2, WP1, WP5, WP6, WP9, WP10, WP11, WP12, WP8, WP7)

a.2) Start with the Z flange and weld from one side to the other end. Then the sequence is: (WP7, WP8, WP9, WP10, WP11, WP12, WP7, WP8, WP9, WP10, WP11, WP12)

b.1) Start with the X flange and lock the middle points first and approach to both sides. Then the sequence is: (WP9, WP10, WP11, WP12, WP8, WP7, WP4, WP3, WP2, WP1, WP5, WP6)

b.2) Start with the X flange and weld from the one side to the other end. Then the sequence is: (WP7, WP8, WP9, WP10, WP11, WP12, WP7, WP8, WP9, WP10, WP11, WP12)

Further investigation and simulation of each case will be conducted in RD&T in order to verify the data collected from the interviews. Detailed description will be presented in Chapter 5.

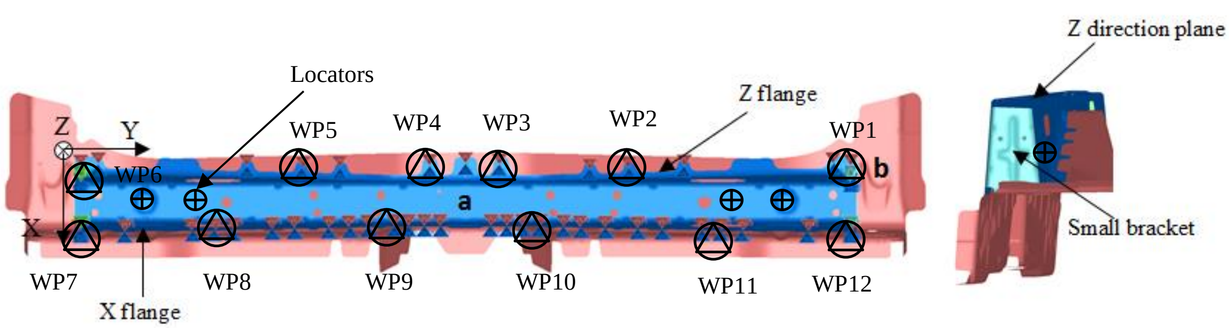


Figure 14: Geo-spot selection on Case B

(a) Blue part (b) Red part

4.2. Interview data analysis

In this section the results achieved from the analysis of the gathered data from the interviews are explained and a Geo-Spot Selection Workflow (*GSSW*) is presented.

4.2.1. Root cause analysis

By summarizing and investigating the results from Table 2, the relevance between the fifteen *CFs*, presented in Section 3.3.4, and the three criteria, presented in Section 3.2, are described by the hierarchy tree (see Figure 15). The tree shows that all of the investigated *CFs* have more or less influence on the *Criterion 1* (Assuring geometry robustness).

Some *CFs* were eliminated from the *Criterion 2* and the *Criterion 3*, because the interviewees did not think that all *CFs* will contribute to them. In the *Criterion 2* (Rigidity of assembly), *CF5* (Number of parts) and *CF12* (The geometry of welding gun) are filtered out from *CG1* (Design concepts) and *CG4* (WPR), respectively. Furthermore, *CF5* (Number of parts) and *CF3* (Locating scheme) are taken out from the *Criterion 3* (Low influence of respots), because in the respot station the assembly is already joined by the geo-spots and a gripper is holding it. In addition, it was agreed by most of interviewees that *CG4* (WPR) has no influence on the *Criterion 3*.

I. Hierarchy Tree of Root Cause Analysis

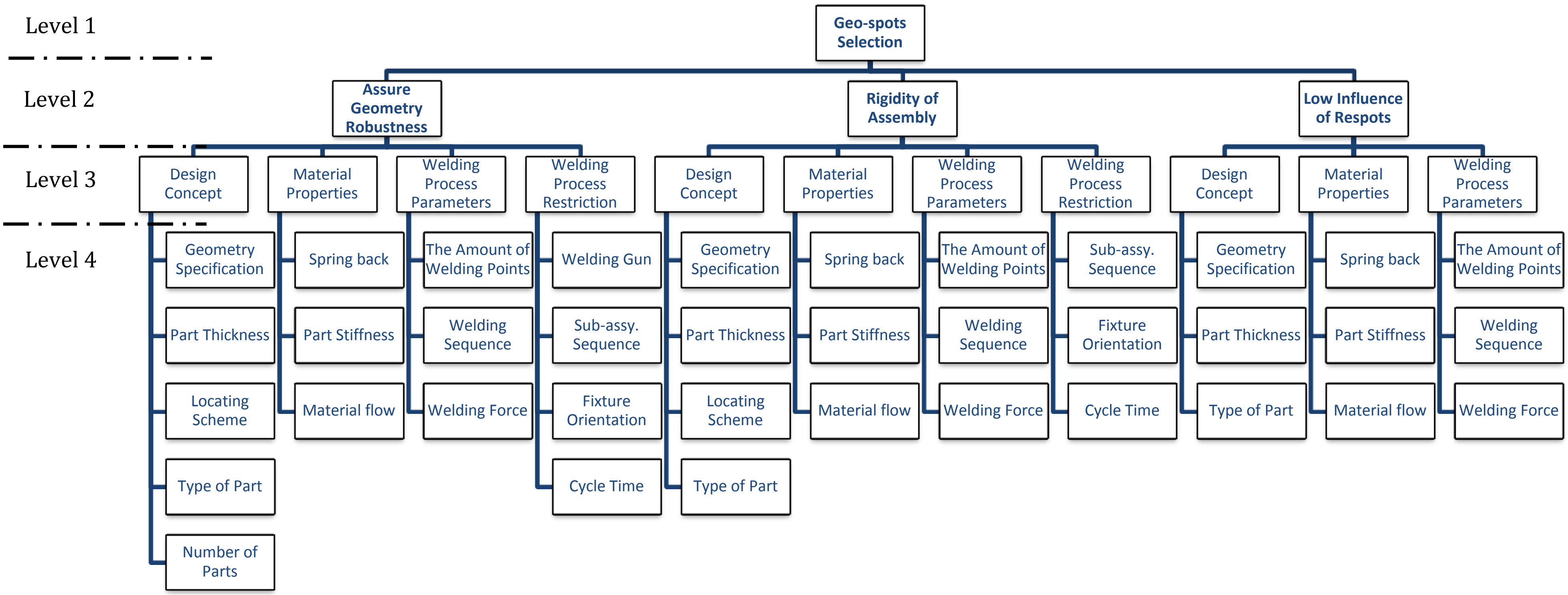


Figure 15: Hierarchy Tree of Root Cause Analysis

4.2.2. The importance-weight of *Consideration Factor* and *Classification Group*

The Hierarchy Tree of Root Cause Analysis (see Figure 14) presents the relations between each factor with three main criteria. Based on the hierarchy tree, the importance-weight of each *CG* and *CF* (on the Level 3 and Level 4) is analyzed using AHP method, which is presented in Table 4. The paired-wise comparisons in AHP are evaluated according to the *Priority of Group* and *Priority of Factor* acquired from interviewees (see Table 3). The given priority indicates the interviewee's preference to *CGs* and *CFs* judged by the same criterion. Lastly, the results are calculated using the AHP template [27].

Level 1 in the hierarchy, presents the goal to select geo-spots.

Level 2 presents the three criteria formulated to evaluate *Geo-spots selection*. Based on interview studies, it was identified that each criterion corresponds to the specific station in the pre-assembly cell (see Figure 3). *Criterion 1* (Assure geometry robustness) is the main criterion that refers to the complete process in pre-assembly station, which contains both geo-station and respot station. *Criterion 2* (Rigidity of assembly) is evaluated after the parts are welded by geo-spots so this criterion refers to geo station. *Criterion 3* (Low influence of respots) is preferable in respots station, because the geometry of assembly has been secured by geo-spots. Thus, in this level, the *Criterion 1* is assigned 50% importance-weight; *Criterion 2* and *Criterion 3* are assigned 25% importance-weights, respectively.

Level 3 presents the results of *CGs* calculated using AHP method. The result in Table 4 shows that *CG1* (Design concepts) has the highest importance-weight in all criteria. It indicates that this group has the greatest influence on the overall goal *Geo-spots selection*. Moreover, the other three *CGs* are more or less equally important (see Table 4).

Level 4, the three most important *CFs* are *CF1* (Geometry specification), *CF4* (Type of part) and *CF3* (Locating scheme) that all belongs to *CG1* (Design concepts) (see Table 4). These *CFs* have a significant influence on the decision of *Geo-spots selection* and are considered primarily. It also explains why *CG1* (Design concept) is more important than any other *CGs*.

I. The importance of each factor

Table 4: The importance of each factor

Geo-spots selection								
1								
Assure geometry robustness								
	Design concept		*Material Properties*		*WPP*		*WPR*	
	29,30%		6,80%		7,60%		6,35%	
	Geometry specification	9,32%	Spring back effects	2,33%	The amount of WP	2,99%	Welding gun	1,49%
50%	Part thickness	2,64%	Part stiffness	2,97%	Welding sequence	3,40%	Sub-assembly sequence	1,95%
	Locating scheme	6,74%	Material flow	1,50%	Welding force	1,21%	Fixture orientation	1,05%
	Type of part	8,82%					Cycle time	1,85%
	Number of parts	1,90%						
Rigidity of assembly								
	Design concept		*Material Properties*		*WPP*		*WPR*	
	14,65%		3,40%		3,80%		3,18%	
25%	Geometry specification	5,11%	Spring back effects	1,16%	The amount of WP	1,49%	Sub-assembly sequence	1,15%
	Part thickness	1,01%	Part stiffness	1,49%	Welding sequence	1,70%	Fixture orientation	0,78%
	Locating scheme	3,65%	Material flow	0,75%	Welding force	0,60%	Cycle time	1,24%
	Type of part	4,48%						
Low influence of respot								
	Design concept		*Material Properties*		*WPP*		**Level 1**	
	16,60%		3,63%		4,78%		**Level 2**	
25%	Geometry specification	7,29%	Spring back effects	1,24%	The amount of WP	1,88%	**Level 3**	
	Part thickness	2,56%	Part stiffness	1,58%	Welding sequence	2,13%	**Level 4**	
	Type of part	6,74%	Material flow	0,80%	Welding force	0,76%		

The Table 4 is structured based on AHP tree (see Appendix B).

II .Priority list

The importance-weight of each *CF* is summed up to the priority list presented in Figure 16. The list shows the overall opinions from all interviewees and it can be the guideline for engineers to select geo-spots by considering all these factors step by step.

The three *CFs* of *CG1* (Design concepts), *CF1* (Geometry specification), *CF4* (Type of part) and *CF3* (Locating scheme), should be considered firstly, since they significantly affect the outcome of the assembly. The *CG3* (WPP) is on the second place to be considered, which includes *CF10* (Welding sequence) and *CF11* (The amount of welding points). Moreover, *CF8* (Material properties) should be considered as well; especially when it comes to special materials with strong stiffness such as boron steel or other materials with unique characteristics. Last but not least, *CG4* (WPR) does not have a high priority. Engineers regarded *CG4* (WPR) as the pre-conditions of the process and the process design is not easily changed. Additionally, *CF11* (Welding force) has very low influence on selection of the geo-spots. Thus, *CF11* (Welding force) is taken out from our model of the process of geo-spots selection.

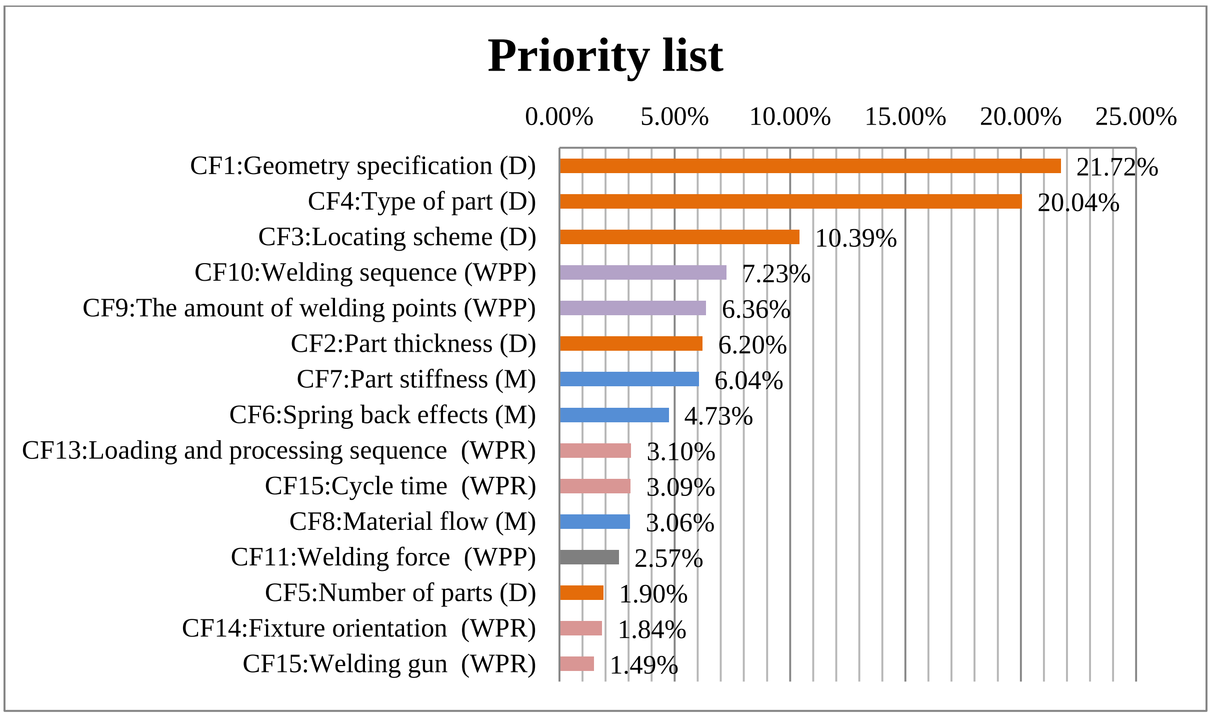


Figure 16: Priority list

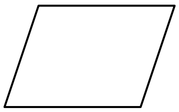
4.2.3. Geo-Spot Selection Workflow (GSSW)

The *Geo-Spot Selection Workflow* (GSSW) is created based on the results of the interviews and the priority list, coupled with the verified hypotheses. In order to formulate the multi-disciplinary task of geo-spot selection a flow chart mapping the work procedure is presented.

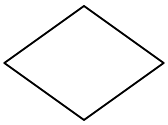
I. The shapes in the workflow

In order to prioritize the order of the appearance of each contributing element in the flow chart, the results of the AHP analysis are taken into consideration. The model is built based on commonly used flow chart symbols. The meaning of each symbol appearing in the flow chart is explained below.

The model starts and ends using this symbolic figure.

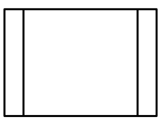


The parallelograms are input/output; In this workflow, input and output is a set of welding points, these sets could consist either geo-spots, respots or combination of both.



The diamonds are the decision points where a decision or a trade of needs to be made.

The rectangles are the actions or the processes.



The rectangles with the margin are the predefined processes; in these shapes the verified hypotheses are coupled into the model.

The documents include necessary information to look through and consider before taking actions.

II. The steps in the workflow

The *GSSW* is divided into four steps, shown in different colors, and one additional tool box is embedded to describe the step of physical matching and trimming performed to solve the geometric issue in the process (see Figure 18). The workflow is generated based on the analysis of the interview results and each process takes in the order of the *Priority list* (see Figure 16) that is summarized by the overall opinions from all engineers.

Step 1

In order to start the task of geo-spots selection, firstly the CAD models are received. These models contain all necessary information, including the welding points on the parts and the information about the locating schemes. These data are the main inputs used in the first step of selecting geo-spots.

The first process is to understand the important features and the requirements set on the sub-assembly. By understanding the part type, the engineers can get a feeling about their required functions and also relate them to the requirements. Geometry specification should also be checked for understanding the main features needed to be secured in the welding process.

After knowing the important features of the parts, the next process is to analyze whether the locating schemes can satisfy the requirements. The purpose of the locating schemes is to lock the parts in all degrees of freedom and to minimize the gaps between the mating surfaces to be joined. In order to satisfy this purpose the locators are positioned with a suitable distance among each other. However, due to the part complexity or assembly restriction it is not always physically possible to position the locators on the desired place, therefore while selecting geo-spots, it should be considered if the locators are on their optimal position or not. If needed, it is possible for the engineers to negotiate with the designer about changing the locators to a more suitable position.

Analysis of the part locating schemes gives a first hint on how the required geo-spots should be selected. Those preferable points are the initial proposal of geo-spots, which are the inputs to the next step where further analysis will be conducted.

Step 2

Based on the judgment in step1, in order to assure that the geometry of the assembly will be stiff/stable after releasing the clamps and detaching it from the fixture the first set of geo spot should be selected close to the locators in accordance with Hypothesis 1. This is applicable if the locating scheme has the ability to satisfy the requirements set on the assembly.

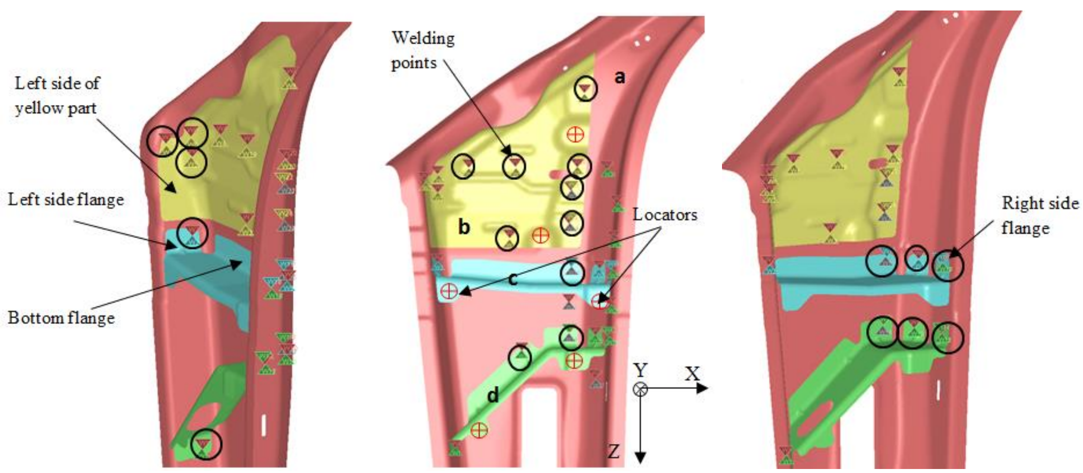


Figure 17: Geo-spot selection of Case A

On the other hand, if the locators are not on their optimal position and they cannot satisfy the geometrical requirement, then the geo-spots have to be chosen to compensate for this. By analyzing upper middle reinforcement part in Case A (blue part), it can be seen that the locators are only positioned on the small flanges, marked with ⊕ in Figure 17. According to Hypothesis 2, it is preferred to have the locators placed on the bottom flange pushing it down and make it follow the geometry of the base part, while there are no locating elements on that flange. Therefore, it is inferred that there should be one geo-spot on the bottom flange to make the geo-spot act as a locating scheme (also Section 4.1.2, Sketch 5: Hypothesis 5).

The geo-spots should assure the geometrical requirements of the part in the light of Hypothesis 2. Moreover, in order to make the geo-spots act like a locating system, they should be spread over the part to lock the main axis of the direction. This is according to the Hypotheses 3 and 5 that were verified by interviews. This approach comes from the rules of designing a proper locating scheme for the part.

However, sometimes those desired weld points cannot be selected as geo-spots, because the elements in the *CG4* (WPR) will restrict the choice. Therefore, these restrictions are needed to be considered at this process as follow:

a. Loading and processing sequence and the number of the parts to be assembled
b. Fixture orientation
c. Geometry of the welding gun

Knowing the loading sequence helps to identify the “hidden” points. These points are the ones that will not be available for welding in later assembly steps, thus they have to be taken in a certain order, because some parts will cover them in subsequent processes. For instance, in Case A, the points on the right flanges of the middle reinforcement parts (Blue and green parts) are hidden points. Therefore, these points need to be selected as geo-spots although sometimes they do not contribute to locking the geometry.

Fixture orientation can help us realize the way that the parts are being loaded in to the fixture. Gravity is sometimes an issue. Therefore, some geo-spots will be needed to oppose gravity force.

Geometry of the welding gun needs to be kept in mind during the selection process. According to the experience, a clearance of 40 mm around the locators is required for the geo-spots selected close to the locators. These clearances are required to minimize the risk of collision between welding gun and the locating elements.

After filtering out some point or adding some required points because of the prerequisites a new set of points can be generated at the end of the step 2 which includes the points close to the locators (or the points acting as new locating system), the preferable points and prerequisite points. In addition, there are still some other preferable points that will be further investigated.

Step 3

Following the priority list, see Figure 16, part thickness and part stiffness need to be addressed next. In order to get a complete understanding on how the material will behave and what kind of geometry outcome that should be expected after welding, material properties need to be kept in mind. This is mainly to identify the master and slave parts of the assembly. Based on Hypothesis 6, the master part determines the geometry and makes the slave part follow its geometry. For instance, the lower reinforcement part in Case A (green part) can show the importance of part stiffness influence. On the both sides of this part, there are two flanges. While the flange on the left side is flimsy and can be bended during welding, the flange with the reinforcement (bird-beak) on the right side will drag the part to the right after welding (see Figure 17).

Therefore, the point which helps to follow the geometry of the more important part should be selected as geo-spot. However, the number of welding points added to the set should be kept within the required cycle time. If the selected geo-spots until this step can be welded within the cycle time, then the initial set of geo-spot can be generated. On the other hand, if more points than the allowed cycle time have been selected so far, there are two options. Negotiating for adding more robots to the geo station cell, to be able to weld those points within the cycle time, or start from initial set of points and reconsider some of the choices made.

Step 4a

After deciding on the initial set of geo-spots, the welding sequence of the selected points has to be considered. The process of the sequence optimization today is achieved by performing the physical matching and trimming procedure which was described before (see Section 4.1.1). The welding sequence is considered as a sub-process within the complete process of physical matching and trimming. It is assumed that the major conflicts between the mating surfaces are resolved before the study of a suitable sequence is performed.

Different welding sequences are analyzed by physical testing. Firstly, the geo-spots are being set on the part in a preferred order and the geometric outcome is analyzed. If there are no geometrical issues on the part then the respot will be welded and the outcome will be analyzed again. But in case of geometric issues, another loop of tasks is executed for overcoming those issues. This loop is described by the box "*Additional Tool Box" for* solving geometrical issues added in the workflow.

Additional Tool Box

To reduce the gaps generated because of the fabrication error in the parts, material flow while welding should be considered thoroughly. Firstly, the present locating scheme should be analyzed to check if the material flows in a proper way or if the clamps need to be changed in a certain way to allow the material flow based on Hypothesis 4. Moreover, material thickness should be considered, since it will influence the material behavior while welding the parts. In short, these additional points selected as geo-spots shall force the material to flow in the proper (and desired) direction.

After this process, if there still are geometric issues on the parts, the part demands should be adjusted. The selection process should be reconsidered again after adjusting the demands, however many of the previous steps can thereafter be performed faster, since the acquired knowledge through the previous processes can be reused.

After solving the gap problems between the parts, then the spring back effect should be analyzed. If there are problems with the spring back on the welded part, some more additional points should be selected in the problematic areas in order to constrain the spring back effect (see Section 4.1.2, Hypothesis 7).

While adding additional geo-spots to solve the geometric issues, the limitation of cycle time in the station should always be taken into consideration. Therefore, if there are more points than allowed by the cycle time a trade-off between the initial selected geo-spots and the added points should be made to overcome geometrical issues.

Step 4b

Finally, the respots of the assembly can be welded and the geometry of the assembly should be checked again. In case of existence of remaining geometrical issues, the welding sequence box should be iterated. After making sure that there are no geometric issues on the parts, the settled set of geo-spots could be proposed and conclude the process of geo-spot selection.

III. GSSW

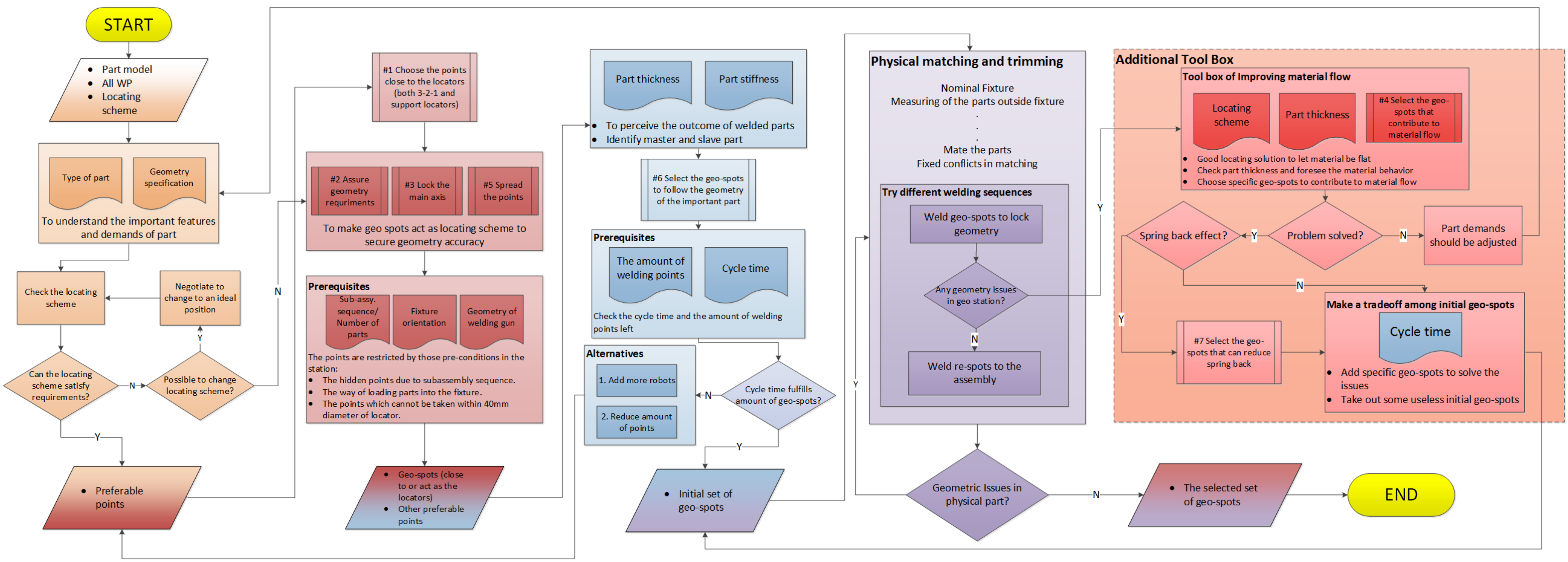


Figure 18: Geo-Spot Selection Workflow (GSSW)

5. PROPOSED METHOD OF GEO-SPOT SELECTION

In this chapter, the proposed method of geo-spot selection is described (see Figure 19). More detailed description of *SI-GSSW (Simulation Integrated Geo-Spots Selection Workflow),* explaining the simulation integration of *GSSW* is given. In addition, the results achieved from each simulation step and the final decisions of the selected set of geo-spots using the proposed method are presented.

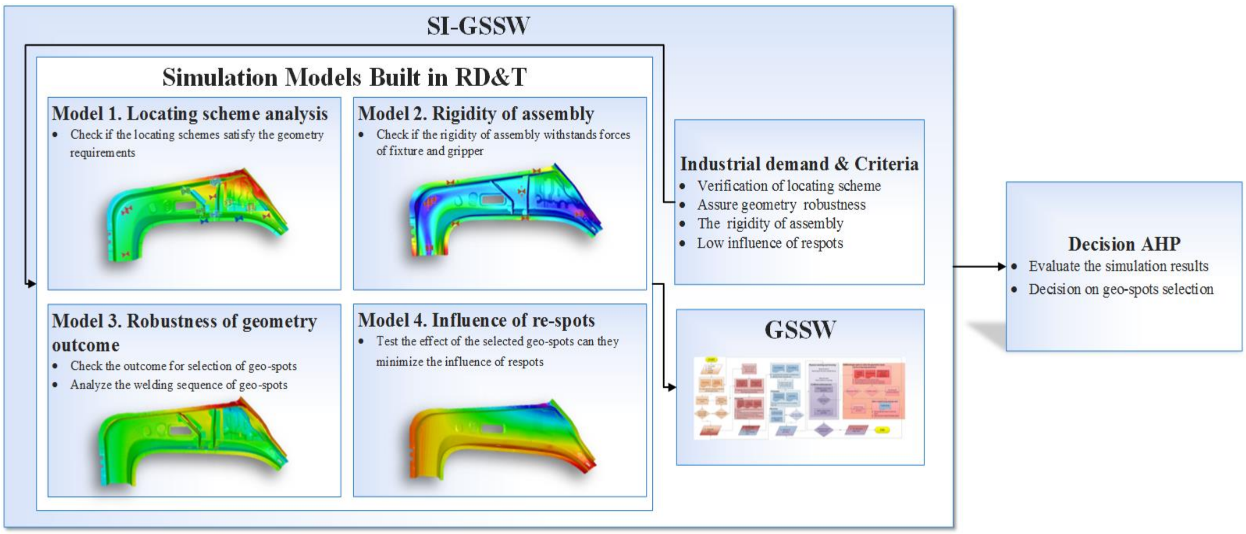


Figure 19: Proposed method

The proposed method consists of two steps, *SI-GSSW* and *Decision AHP*. Based upon the collected data from interviews and the criteria presented in Section 3.2, simulation models are developed in RD&T to simulate and verify each demand and criterion. Moreover, these simulation models will be integrated with experience based workflow – *GSSW*. The combination of *GSSW*, *Industrial demand & Criteria* and *simulation models built in RD&T* result in *SI-GSSW* by which different sets of geo-spot can be proposed and simulation results for a selection of geo-spots can be achieved. The details of *SI-GSSW* are presented in Section 5.1. Lastly, the simulation results will be used as input to the *Decision AHP* and the simulation results of each set will be evaluated in this step. Finally, the decision of geo-spot can be verified (see Section 5.3).

5.1.The Simulation Integrated Geo-Spot Selection Workflow (SI-GSSW)

The *GSSW* presented in Section 4.2.3 was only derived from engineers' experience. The process of selecting geo-spots is an iterative process, still lacking sufficient supports in the decision making. The goal of the project is to provide a convincing simulation integrated method to evaluate the choice of geo-spots and to improve the method *GSSW*.

For each criterion (see Section 3.2), a specific simulation model is built to verify the made selection. In addition, the eligibility of locating scheme has a profound influence on the variation of the whole assembly. Therefore, a simulation model verifying the locating scheme is also built to assure that the locating scheme can satisfy the geometrical requirements set on the assembly. All the models in this project are established in RD&T software, which are implemented on the both cases respectively (see

Section 5.2). Furthermore, these simulation models will be integrated with *GSSW*. Through combining advanced simulation support and proven industrial experience, a comprehensive work procedure - *SI-GSSW* is presented (see Figure 20).

First and foremost, with the help of RD&T, the locating scheme is verified using variation simulation which can be used as a support for the negotiation of changing the locating system. Therefore, the first simulation model is designed to evaluate the eligibility of the locating system. The result of this simulation can support the decision in the first step of workflow, to predict the variation in parts caused by the locators and their placement. The necessary changes of the design or the process can be detected in the early phase of the selection process (see Section 5.2, Model 1).

Secondly, the Criterion 2 of the geo-spots selection specifies that geo-spots should make the assembly withstand the applied forces in the subsequent processes. Going through the workflow of experience, it can be seen that there is no process specifically designated for this purpose. However, in the physical matching and trimming step, forces that are caused by gripper and fixture will be exerted to the assembly. The idea of analyzing rigidity should not be completely neglected in the process. Thus, a model describing the rigidity of the parts needs to be included in the working procedure. A variation simulation model for testing the rigidity of assembly after geo-spot welding will support the decision of the second criterion (see Section 5.2, Model 2).

Furthermore, a decision regarding the geometric issues caused by the selected geo-spots needs to be made. In the current procedure, the one and only approach to analyze these issues is through physical trial, which occurs in the iterative steps of physical matching and trimming process. The third model is built to examine the geometry outcome of assembly and it will be implemented in the workflow. This model corresponds to Criterion 1 (see Section 5.2, Model 3).

Lastly, the decision regarding the geometric issues after setting the respot points on the assembly needs to be supported with the help of the fourth simulation model. The fourth model is built to simulate geometry outcome of the assembly after welding both geo-spots and respots. The result of this model will help the engineers to decide if the expected outcome has been achieved simulating the whole process. In addition, with the help of this model, Criterion 3 will be evaluated (see Section 5.2, Model 4).

In short, the selection of geo-spots will be verified and tested by simulating the process in RD&T. By visualizing the results of the simulations, the errors in the process could easily be observed and tracked. The workflow of *SI-GSSW* is depicted in Figure 20.

Simulation Integrated Geo-Spot Selection Workflow (SI-GSSW)

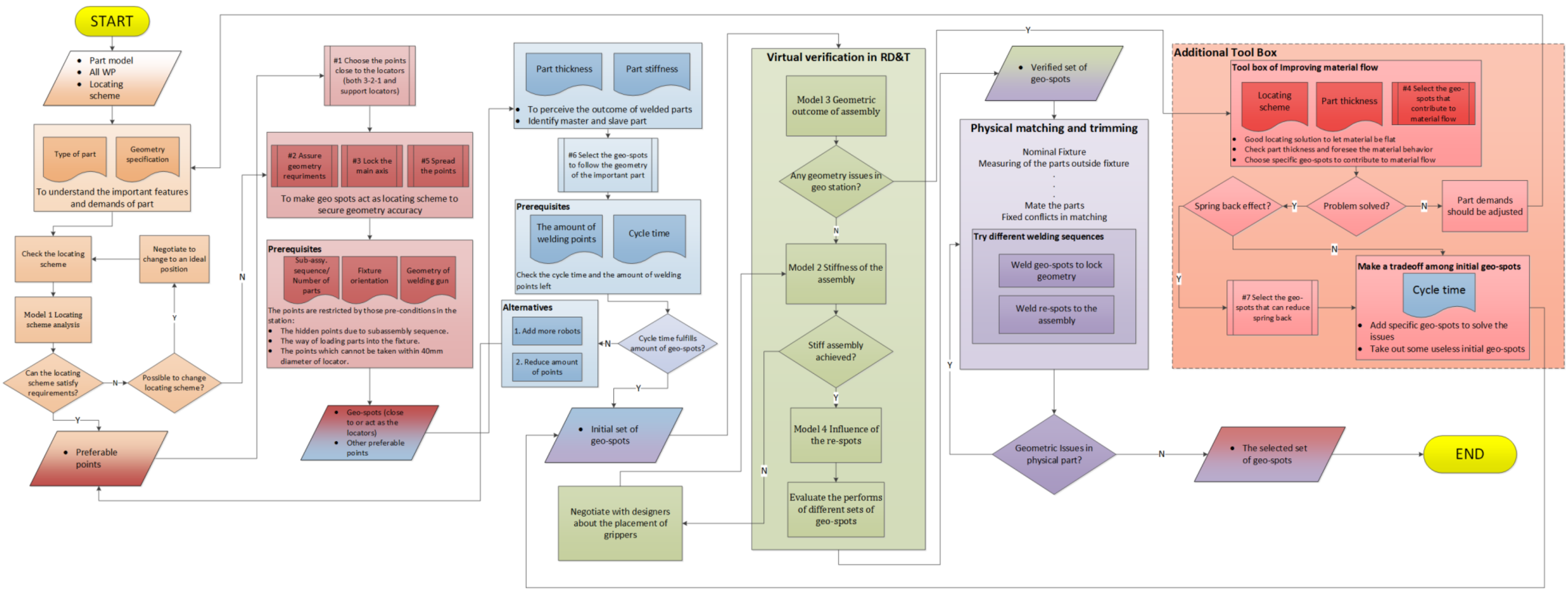


Figure 20: SI-GSSW

5.2. Simulation models in RD&T

The reasons behind building each simulation model have been discussed in Section 5.1. *SI-GSSW*, presented in Figure 18, depicts the use of each model in the workflow. This section describes the details about each model and explains how the CAT- tool RD&T are used to fulfil the purpose.

Model 1: Locating scheme analysis

The Model 1 is intended to verify the locating scheme of non-rigid sheet metal assembly and investigate whether it can help satisfy the geometrical requirements. This model simulates the effect of clamps and fixture elements when the compliant part is located in the N-2-1 system (over-constrained). The effect of clamps and support points should be considered since these fixture elements might deform the parts and enlarge part variations in the final assembly. Sensitivity analysis is executed to examine how sensitive the sheet metal assembly is when unit disturbances are exerted to the locating scheme. The analysis of part variations caused by the locating scheme will help the process of improving the locating scheme; therefore those changes can be implemented earlier in the manufacturing engineering process.

Model 2: Stiffness of the assembly

The Model 2 is designed to test the rigidity of the assembly and to analyze whether the assembly can withstand the forces of subsequent processes. In pre-assembly station, when the parts have been welded together by geo-spots, the assembly will be released from the clamps. Then, a robot gripper comes to fetch the assembly that is still held by the fixture. This model is used to simulate how much variation will be caused, when both gripper and fixture is holding the assembly. Those forces from gripper and fixture could deform the assembly and increase dimensional variations.

In order to analyze how each geo-spot set can contribute to make the assembly stiffer, *super-parts* [10]of the geo-spot welded assemblies are made. Unit disturbances are exerted to the gripper and the fixture and variation simulation is conducted in RD&T. The results of this model can support the judgment of assemblies' stiffness after of geo-spots welding. The placement of the locators in the gripper can also be evaluated using this model.

Model 3: Geometric outcome of assembly

The geometry outcome after the geo-spot welding can be analyzed by Model 3. It means that in this model different sets of geo-spots are going to be evaluated. The initial sets of geo-spots on the part can be generated using *SI-GSSW* (see Figure 18). The variation simulation for different sets of geo-spots will be conducted in RD&T and the results of simulation will be analyzed. Moreover, the welding sequence of the selected geo-spots can be analyzed based on this model as well. The result achieved from the sequence and simultaneously welding models can be compared. Finally, the outcomes of several sets of geo-spots are analyzed and the good candidate sets are selected for further analysis in the next step of *SI-GSSW*.

Model 4: Influence of the respots

As discussed before, one criterion for geo-spots selection is to reduce the influence of respot points, which can be analyzed in Model 4. The simulation results generated from Model 3 are exported and used as a base for this model. The assembly has been welded by selected geo-spots. After assigning the respots

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[10] Super-part refers to a part that is made from an assembly. Super-part might comprise several parts which are welded together.

to the assembly, variation simulation is conducted again. To analyze the influence of respots a comparison of simulations results of Model 3 and Model 4 is conducted, which visualizes the variations of assembly before and after respots.

5.3.Decision AHP

By summarizing the results of all simulation models, the decision matrices (D) for the choosing the best set of geo-spots can be constructed. In these matrices, the decision criteria are the three models; rigidity analysis (Model 2), geometric outcome of assembly (Model 3) and influence of the respots (Model 4). Different sets of geo-spots are regarded as alternatives in the decision making (see Section 2.3.2, Equitation 13).

$$D = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} \end{bmatrix} \tag{16}$$

The weight of each criterion is assigned (see Section 4.2.2). The first criterion (assuring geometry robustness and product functions), which is related to the third model has the *importance-weight* of 0.50. The other two criteria (assuring rigidity of parts and minimizing the influence of the respots) connected to model two and model four, have both the importance weight of 0.25. These values compose the weight array $\widetilde{W}$.

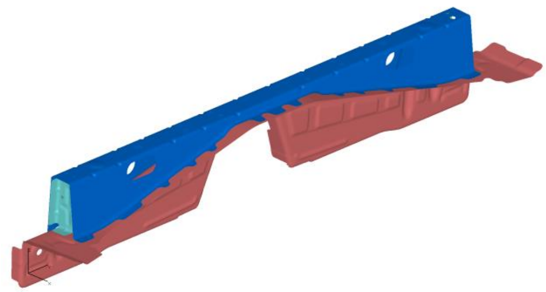
$$D_n\widetilde{W} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix} \tag{17}$$

Finally, the decision values of selected geo-spot set can be calculated by multiplying the normalized D_n matrix with the weight array. The set corresponding highest value of d_i can be selected as the best set. This is the result of the comprehensive analysis.

5.4. Application to case study

The following simulation models were built to simulate the assembly of Case A and Case B, respectively. Detailed information for each case is presented in Table 5 below.

Table 5: Case study characteristics

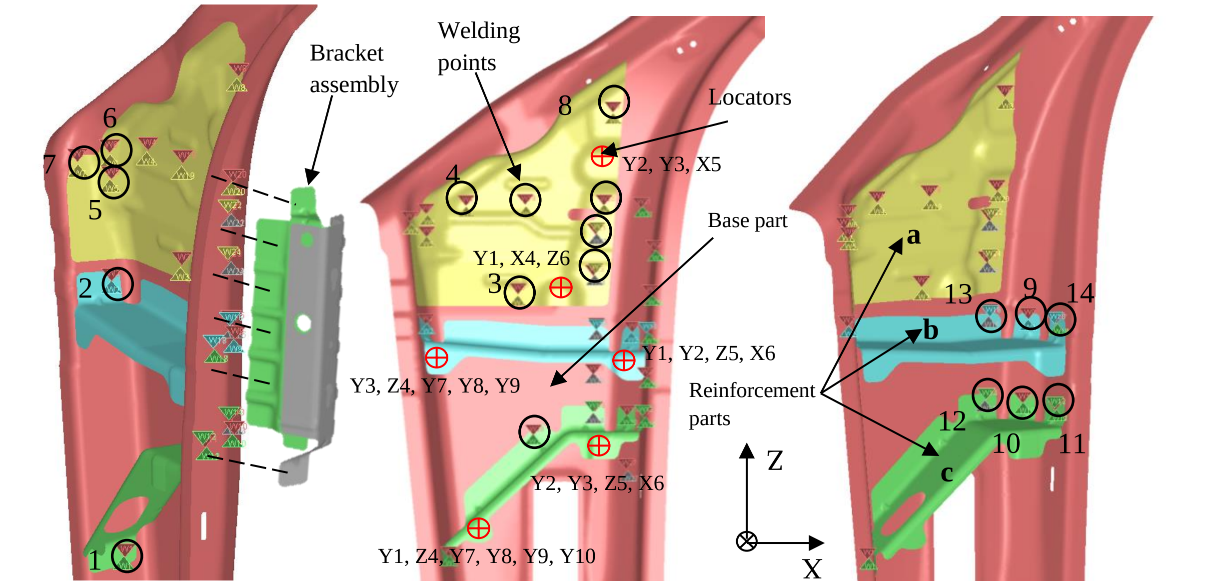
	Case A	*Case B*
Description	A-pillar assembly	Cross member assembly
Pictures		
Simulation models	1. Locating scheme analysis 2. Stiffness of the assembly 3. Geometric outcome of assembly 4. Influence of the respots	1. Locating scheme analysis 2. Stiffness of the assembly 3. Geometric outcome of assembly 4. Influence of the respots
Parts of assembly	Base part 3 reinforcement parts Supper part assembly: 2 brackets	Upper part (blue part) Lower part (Red part) 2 reinforcement parts
Number of locators in fixture	Base part: 5 Reinforcement parts: Yellow part: 4 Blue part: 7 Green part: 7	Upper part: 6 Lower part: 6 2 reinforcement parts: 6
Number of locators in the gripper	Base part: 6	Lower part: 6
Number of geo-spots and respots	12 spot welds for geo station 19 spot welds for respot station	16 spot welds for geo station 41 spot welds for respot station

5.4.1. Case A geo-spot selection

Before executing the analyses, several initial sets of geo-spots were selected according to *SI-GSSW*. There were four sets of geo-spots chosen for analyses of Case A. Each set of geo-spots contains 12 points welded in the geo station, based on the limitation of cycle time.

Table 6: Selection of geo-spots - Case A

Case A: Welding points on the assembly



Geo-spots selections			
First set	*Second set*	*Third set*	*Fourth set*
[3 4 5 8] [2 9 13 14] [1 10 12 11]	[3 5 6 8] [2 9 13 14] [1 10 12 11]	[3 5 7 8] [2 9 13 14] [1 10 12 11]	[3 5 6 7 8] [2 9 13 14] [10 12 11]

The geo-spot sets are selected from the pre-defined WPs on the assembly. The geo-spots of Case A are separately located on three reinforcement parts in the assembly. On the yellow part (a), there are three common points in each set that are WP3, WP5 and WP8. WP3 and WP8 are near the locators locking the part close to nominal in the XZ plane as defined by the fixture (The position of the locating scheme and their directions are shown in Table 6). These two points together with WP5 construct the biggest triangle area on the part and make the part attach to the base part. The other points (WP4, WP6 and WP7) are picked to secure the key feature on the part such as the corner of left side.

On the blue part (b), the selection is limited to four WPs. WP9 must be welded first due to the loading sequence. The bracket assembly will be positioned in the fixture after WP9 is taken. Afterwards WP9 will be hidden by the *bracket assembly*. Then, WP13 should be taken to lock the main direction of the blue part (b). To secure the right corner, WP14 should be taken afterwards to make the whole part attach to the base part. WP2 is selected to lock the blue part in X direction. If taking the sequence into consideration, WP2 should be welded lastly, since the small flange where WP2 is located, is flimsy and have the ability to bend.

On the green part (c), all those points are selected based on the same reasoning as the ones on the blue part. The only difference is that in the fourth set, WP1 is taken out from the set in order to add an extra geo-spot to fixate the corner of the yellow part. The small flanges on the left side between the green part and the base part can be welded in the respot station.

5.4.2. Case A simulation results

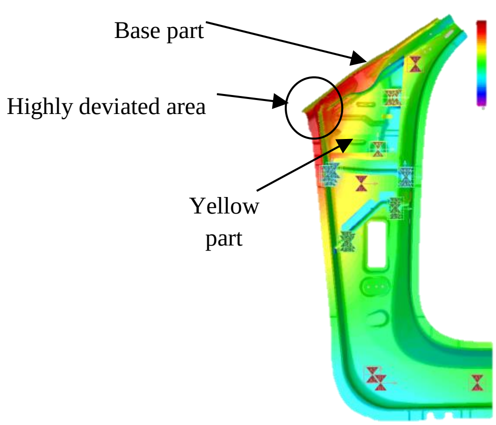
Model 1: Locating scheme analysis

The most important geometrical requirement of Case A is to assure the geometrical accuracy of the flanges around the base part. The locating scheme of the sub-assembly must meet the requirement and fixate the parts with low variations. As the results in Table 7 shows, the left corner of the base part turns intensively red which indicates the high deviation in that area, when the part is putting into the original locating scheme (location scheme of the base part and their directions are shown in Table 7, for the rest of the parts see Table 6).

It can be inferred that the design of original locating scheme on the top reinforcement part has a main impact on the part variation. The locators on the top part are densely located on one side of part, while on the left side of part there are no locaters to secure the position. Therefore the existing sensitivity is due to the contact between the base part and the yellow part. Through redesigning the locating scheme, the new strategy is to move one original locator from the right to the left side on the yellow part and only push it against the base part to follow its deviations in X direction (see Table 7). By changing the position of one locator, the part mean deviation is reduced from 0.74 to 0.64 mm and the RMS is reduced from 0.19 mm to 0.15 mm.

Table 7: Model 1 results - Case A

Locating Scheme Analysis

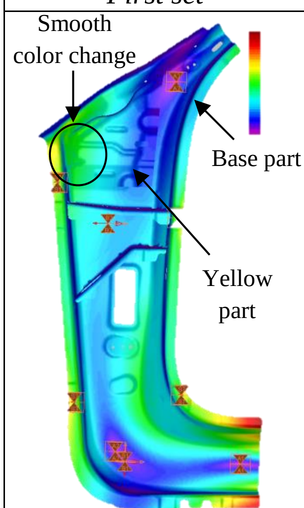
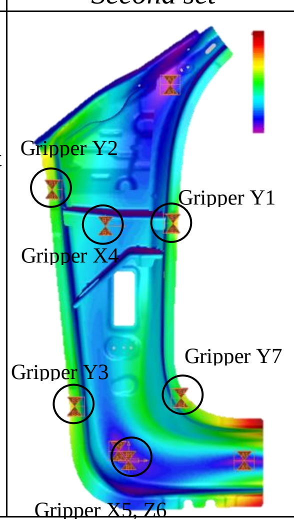
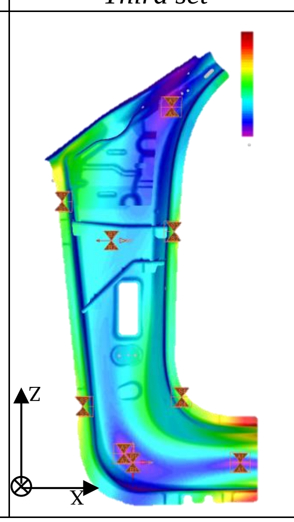
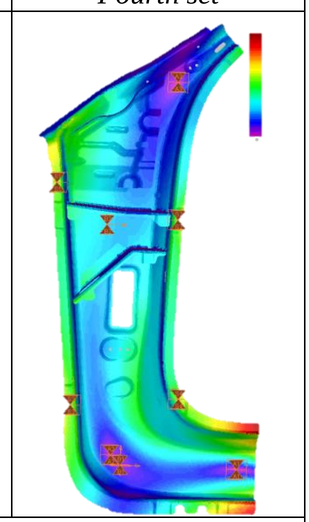
	Original scheme	*Improved scheme*
Case A		
Part Mean deviation (mm)	$[-0.53, 0.74]$	$[-0.54, 0.64]$
Root Mean Square (mm)	0.19	0.15

Model 2: Stiffness of the assembly

Based on the results of Model 2, all four geo-spot sets can provide stiff enough assemblies. The unit disturbances are exerted by both locators and grippers to the parts that are welded by different sets of geo-spots. The expectation of the results from this model is to get smooth colors changes indicating that the parts are following each other.

The four sets of geo-spots will result in smooth color changes. For instance on the yellow part and on the base part the colors are green and changes smoothly to light blue, indicating that the yellow part is following the base part for all the sets (see Table 8). In addition, it can be seen that the applied forces will result in a low level of deformations and that the part variation is within $[0, 1.34]$ mm range. Therefore, it can be claimed that all sets of geo-spots can satisfy the requirement of rigidity for Case A assembly. The results achieved from all the sets of geo-spots are close to each other. This is mainly because the disturbances are applied on the base part, not on the reinforcement parts (the positioning of the gripper and their directions are shown on Table 8).

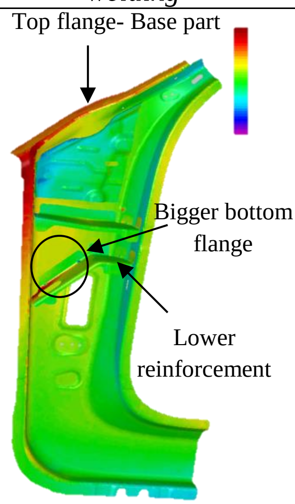
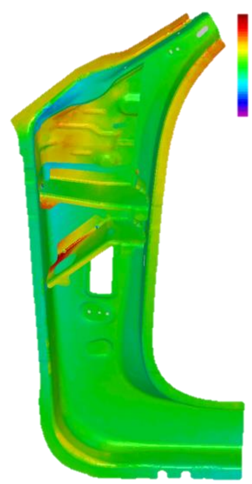
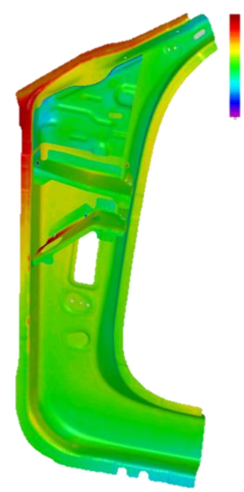
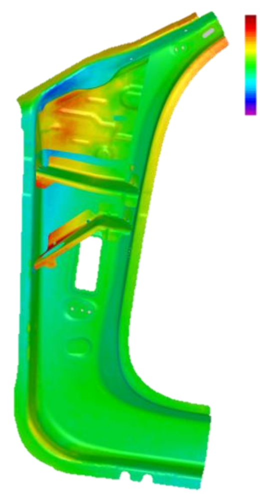
Table 8: Model 2 results - Case A

Stiffness of the Assembly			
First set	*Second set*	*Third set*	*Fourth set*
			
Min.-Max. Part Variation (mm)			
$[0, 1.32]$	$[0, 1.34]$	$[0, 1.34]$	$[0, 1.34]$
Root Mean Square (mm)			
0.39	0.39	0.39	0.40

Model 3: Geometric outcome of assembly

For the Case A assembly, four sets of geo-spots are generated and tested by simulation. Total 12 geo-spots selected in each set were welded on the assembly (see Section 5.4.1). The simulations show that the top flanges of the base part in the first and the third sets have high mean deviation; up to around 2 mm. The outcomes of these two sets are not desirable for the geometrical requirements of assembly. Compared with these two sets, the second set and the fourth set have a better performance on the flanges of the base part that keep the mean deviations down to1 mm. Notably, in the second and fourth set, the part deviation of the lower reinforcement part is higher than on the other two parts, because there is a lack of geo-spots on the bigger bottom flange (See Table 9). Additionally, the RMS of second set is 0.45 mm which is better than any other of the sets. In short, the second set of geo-spots produces the best outcome of geometry by judging both mean deviation and RMS value. The sequence analysis results achieved from the corresponding geo-spots are presented in Appendix C. The comparison between the results of simultaneously welding and sequential welding is discussed in Chapter 7.

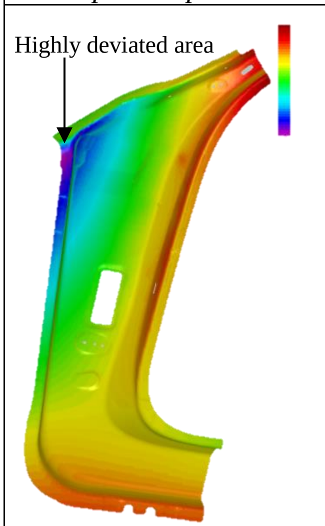
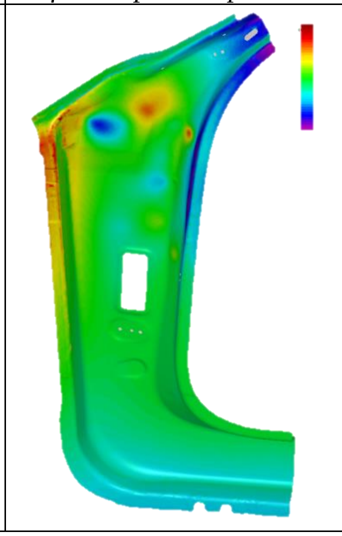
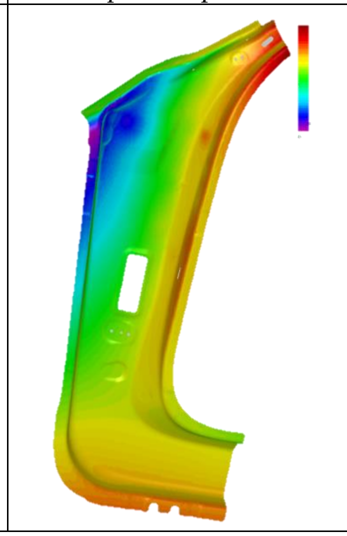
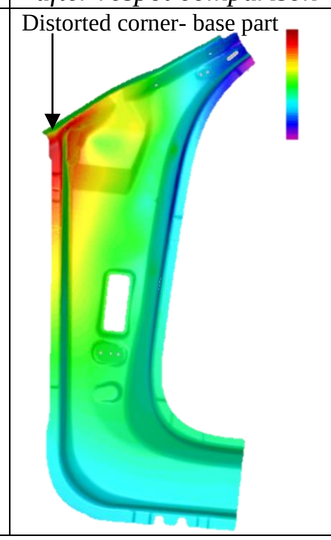
Table 9: Model 3 results - Case A

Geometric Outcome of Assembly			
First set simultaneous welding	*Second set simultaneous welding*	*Third set simultaneous welding*	*Fourth set simultaneous welding*
			
Min.-Max. Mean Deviations (mm)			
$[-2.39, 2.51]$	$[-2.39, 2.51]$	$[-2.33, 2.39]$	$[-2.28, 2.65]$
Root Mean Square (mm)			
0.56	0.56	0.52	0.51

Model 4: Influence of the respots

Table 10 depicts color plots showing the differences in geometry of the base part after adding the respots. The green area has lowest influence from respots; around 0 to 0.80 mm part deviations. The red and purple areas are the zones most affected by respot welding. Especially, the first set and the third set have significant effects of respots on the base part. The part deviations of the first set and the third set are increased up to $-2.84\ mm$ and $-1.94\ mm$ (opposite to the normal direction), respectively. In the fourth set, the left corner of base part flange is still distorted a bit by the respots (see Table 10). In contrast, the second set of geo-spots completely stabilizes the geometry of assembly, showing the lowest influence from respots and also the lowest RMS value.

Table 10: Model 4 results - Case A

Influence of the Respots			
First set before and after respot comparison	*Second set before and after respot comparison*	*Third set before and after respot comparison*	*Fourth set before and after respot comparison*
			
Min.-Max. Normal deviations (mm)			
$[-2.84, 1.24]$	$[-0.22, 0.35]$	$[-1.94, 0.95]$	$[-0.63, 1.12]$
Root Mean Square (mm)			
0.73	0.07	0.53	0.27

5.4.3. Case A decision of geo-spot set

The results from the three simulations using models 2, 3 and 4 can be used to construct a decision matrix as follows:

Table 11: Decision matrix - Case A

Case A	Model 2 RMS	Model 3 RMS	Model 4 RMS
First set	0.39	0.56	0.73
Second set	0.39	0.45	0.07
Third set	0.39	0.52	0.53
Fourth set	0.40	0.51	0.27

Unit: mm

By normalizing the matrix above the following results are achieved for Case A:

Case A	Model 2 RMS	Model 3 RMS	Model 4 RMS
First set	1	0.80	0.096
Second set	1	1	1
Third set	1	0.86	0.13
Fourth set	0.97	0.88	0.26

Unit: mm

Multiplying the weight array ($\widetilde{W}$) to the normalized matrix (D_n) the following results are derived:

First set	0.68
Second set	1
Third set	0.72
Fourth set	0.75

The numbers in this evaluation utilize the variation or deviation data from the simulation results. In the criterion of assembly's rigidity (Model 2), the results of all the sets have approximately equal RMS values. According to the criterion of geometric outcome (Model 3), the second set will have the least mean deviation after the geo-spot welding. The irreconcilable difference among the simulation results of the four sets for Case A is in Model 4. For the criterion of low influence of respots, the second set shows a low influence from the respots (0.07 mm), which makes this set stand out compared to the other three sets.

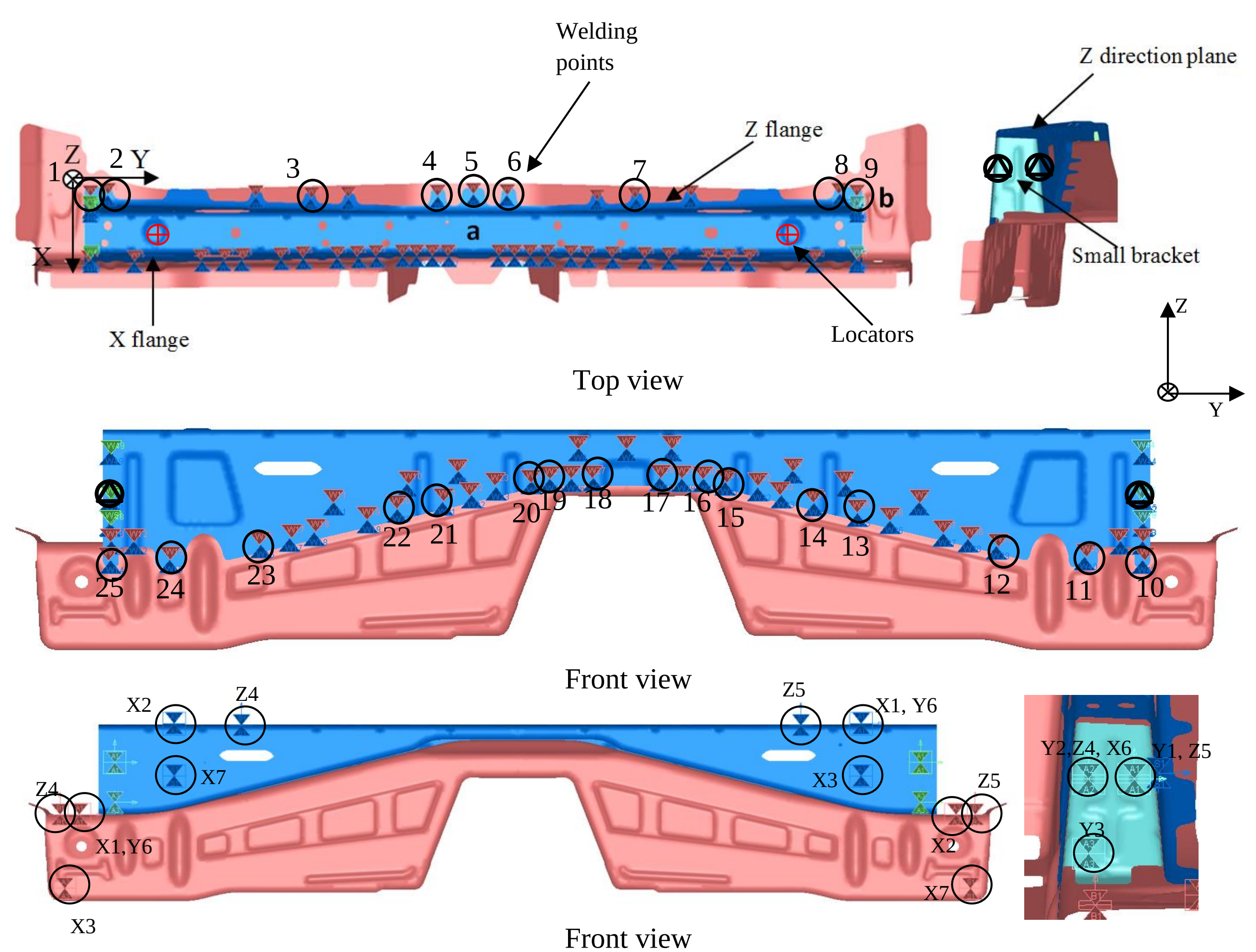
The final decision can be made based on the values of ($D_n\widetilde{W}$). The highest d_i indicates the best alternative considering all the criteria (see Section 2.3). The result from geo-spots on Case A indicates that the second set will result in the best outcome considering the overall performance under the three selection criteria. The fourth set in this comparison has the second highest value and then come the third and first set, respectively.

5.4.4. Case B geo-spot selection

There are four sets of geo-spots chosen for analyses of Case B. Each set of geo-spots contains 12 points welded in the geo station. In addition 4 points, marked with ⧋ in Table 12, are set initially joining the small brackets to the blue part, due to the assembly sequence limitation. The first set on this part is generated by allocating the geo-spots equally on both the Z flange ad X flange. The second set is generated by reducing the number of points on the Z flange and assigning more WPs to the X flange. The third set is implemented for distributing the complementary points (interdependent WPs) over the both flanges.

Table 12: Selection of geo-spots - Case B

Case B: Welding points on the assembly



Geo-spots selections		
First set	*Second set*	*Third set*
[2 3 4 6 7 8 11 13 16 19 22 24]	[1 4 6 9 10 12 13 15 20 22 23 25]	[2 3 5 7 8 11 14 17 18 21 23 24]

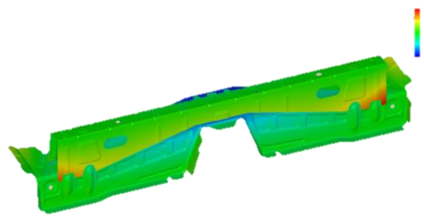
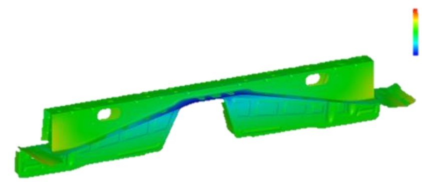
5.4.5. Case B simulation results

Model 1: Locating scheme analysis

The geometrical requirements studied in Case B are to assure that the plane of the upper part is completely horizontal and that the flanges of the lower part are in accurate position. These features need to be secured in order to match with other parts in subsequent processes. Evaluation of the simulation result of Model 1 shows that the original locating scheme is qualified to secure the key feature of the assembly (The position of the locating scheme and their directions are shown in Table 12).

Table 13: Model 1 results - Case B

Locating Scheme Analysis

	Original scheme front	*Original scheme back*
Case B		
Part Mean deviation (mm)	$[-0.46, 0.46]$	
Root Mean Square (mm)	0.14	

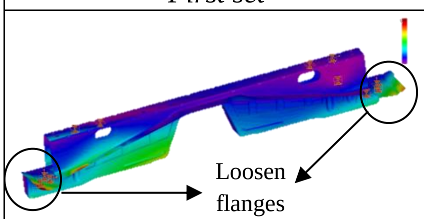
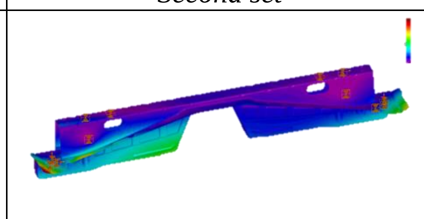
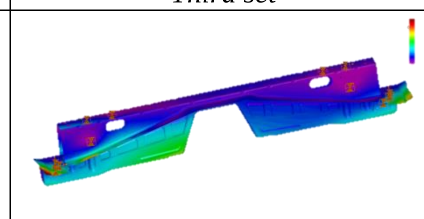
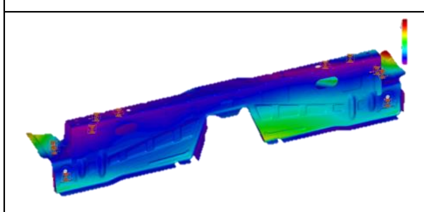
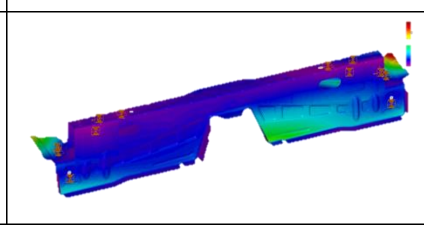
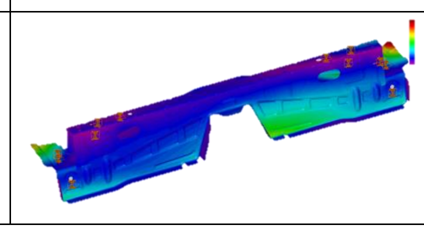
Model 2: Stiffness of the assembly

The results listed in Table 14 show the effect of the fixture and gripper locating schemes on the assembly. The gripper in this case is located on the same position as the locating scheme of the Lower part (red part) (see Table 12). Since the outcomes of the selected sets of geo-spots were quite close to each other, applying the disturbances did not result in large differences in part variations and RMS values when comparing the three selected sets. The RMS values summarizing the simulation results are close to each other and differ only within 0.01 mm. The reason behind this behavior is that the disturbances are only applied on the Lower part (red part), therefore same results achieved on all the three proposed sets.

The highest influence of the gripper on the part will be on the loose flanges on the both sides of the part. This is inevitable since those loosen flanges on the both sides will deviate the most while the welding and forces of the gripper will be applied to the part. Since the gripper locations are close to the loosen flanges on the both ends of the part (see Table 14), then disturbing the gripper position will significantly influence those areas. Moreover, the edges of the loosen flanges are quite flimsy during handling, which is also a reason of high deviation.

Although the forces applied to the assembly by the gripper do not have great influence on the welded areas, there are still some areas that will be affected by this process. Looking at the first set results, it can be seen that the right side of the Z flange will have quite high variation (close to 3mm) which is not favorable.

Table 14: Model 2 results - Case B

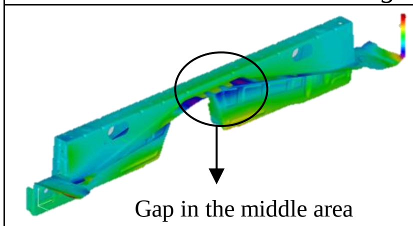
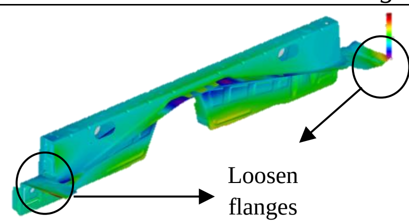
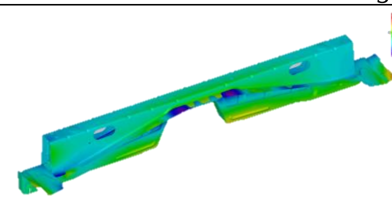
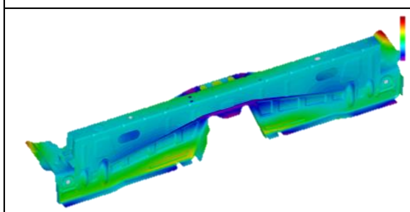
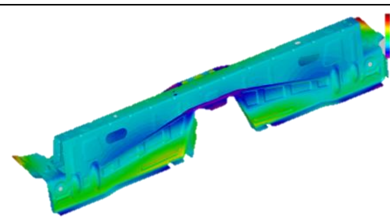
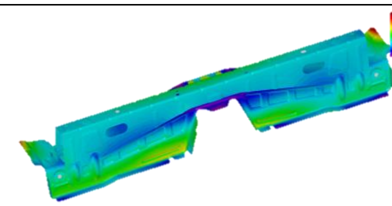
Stiffness of the Assembly		
First set	*Second set*	*Third set*
		
		
Min.-Max. Part Variation (mm)		
$[0, 3.59]$	$[0, 3.59]$	$[0, 3.72]$
Root Mean Square (mm)		
0.76	0.76	0.74

Model 3: Geometric outcome of assembly

Three selected geo-spot sets were analyzed in this model. The results of selecting 12 geo-spots on the part plus 4 welds on the reinforcement brackets (see Table 12) are listed in Table 15. Again in this model the three selected sets of geo-spots generate similar part deviations. All the three sets of the geo-spots generate a gap between the upper part and lower part in the middle area, see Table 15. The outcome of all the three geo-spot sets is around 1 mm distance in that area.

On the both edges of the assembly, the deviation of the lower part will occur again. As mentioned having those deviations is inevitable on the loosen flanges. Having a mean values over 2 mm on the max normal deviation is due to this reason as well. However, on the other areas of the part, the selected sets of geo-spots will result in satisfying deviations. In most of the areas, the mean value does not exceed 2 mm, which is acceptable.

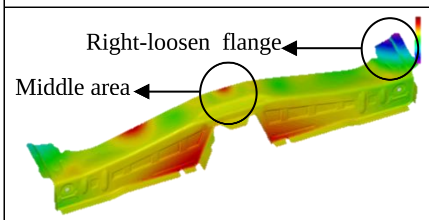
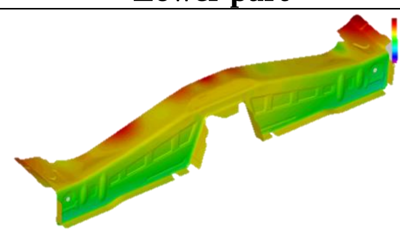
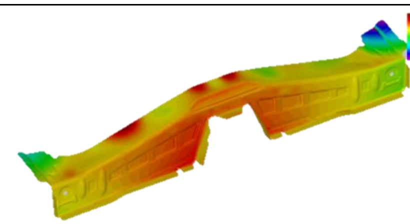
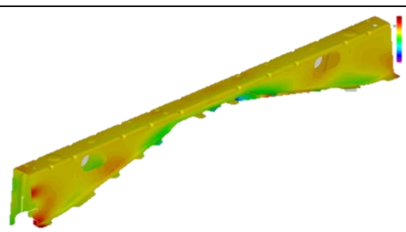
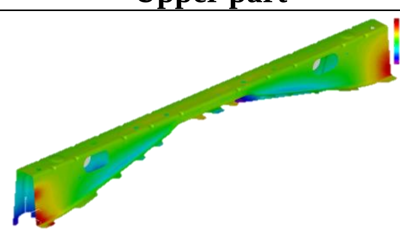
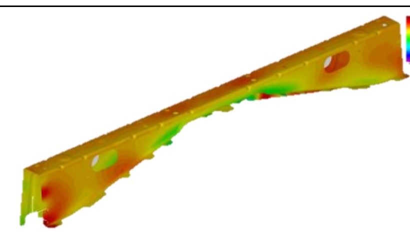
Table 15: Model 3 results - Case B

Geometric Outcome of Assembly		
First set simultaneous welding	*Second set simultaneous welding*	*Third set simultaneous welding*
		
		
Min.-Max. Normal deviations (mm)		
$[-1.44, 2.93]$	$[-1.44, 2.93]$	[-1.44, 2.93]
Root Mean Square (mm)		
0.48	0.48	0.48

Model 4: Influence of the respots

After setting the 41 respots on the Case B assembly and comparing the outcome with the outcome of Model 3, the results presented in Table 16 were achieved. For the first set, the influence of the respot has the mean RMS value of 0.25 mm for the whole assembly. The main influenced areas are the right loosen flange on the lower part; this area has a tendency to bend downwards up to 2 mm. Moreover, the middle area of the lower part which comes in contact with the Z flange on the upper part is influenced up to 1.3 mm upwards (red areas). For the second set, there are even more influence from the respot welding. It can be seen that the loosen flange tends to bend upwards and the middle area deviates up to 1.62 mm in the lower part. On the upper part, the corners deviate in normal direction even more compared to the other two sets (see Table 16). The result achieved from the third geo-spot set also indicates that this set is more sensitive to respot welding compared to the first set. For the third set the upper part is more influenced in normal direction. The RMS value does not differ a lot compared to the first set, but the deviated area on the upper part is broader for the third set.

Table 16: Model 4 results - Case B

Influence of the Respots		
First set before and after respot comparison	*Second set before and after respot comparison*	*Third set before and after respot comparison*
Lower part		
		
Min.-Max. Normal deviations (mm)		
$[-3.69, 1.62]$	$[-3.69, 1.62]$	$[-2.10, 0.96]$
Root Mean Square (mm)		
0.63	0.63	0.33
Upper part		
		
Min.-Max. Normal deviations (mm)		
$[-1.09, 0.49]$	$[-1.25, 0.93]$	$[-1.36, 0.02]$
Root Mean Square (mm)		
0.14	0.35	0.15
The whole assembly		
Root Mean Square (mm)	**Root Mean Square (mm)**	**Root Mean Square (mm)**
0.25	0.49	0.24

5.4.6. Case B decision of geo-spot set

The same procedure for decision-making is applied to Case B and the following results were achieved:

Table 17: Decision matrix - Case B

Case B	**Model 2 RMS**	**Model 3 RMS**	**Model 4 RMS**
First set	0.76	0.47	0.25
Second set	0.75	0.48	0.49
Third set	0.74	0.48	0.24

Unit: mm

The normalized matrix above is calculated for the second model as below:

Case B	**Model 2 RMS**	**Model 3 RMS**	**Model 4 RMS**
First set	0.97	1	0.96
Second set	0.99	0.98	0.49
Third set	1	0.98	1

Unit: mm

Multiplying the weight array ($\widetilde{W}$) to the normalized matrix (D_n) the following results are derived:

First set	0.9843
Second set	0.8587
Third set	0.9896

For the criterion of assembly rigidity (Model 2), the individual comparisons of the models indicate that the results are similar in all the three different models with 0.01 mm differences among the different sets. Moreover, for the criterion of geometric outcome (Model 3), the values are the same comparing the RMS values for all the three sets. Notably, the influence of the respots (Model 4) will determine the selected set of geo-spot on this case again. It can be seen that the influences of the respot on the first and the third set are quite close to each other. However, since the influence from the respots is bigger for the second set, set 1 of set 3 is preferable. In short, the simulation results derived from the Case B shows that the third set will give the best results, considering all three criteria.

6. RESULTS

In this chapter, the results achieved from different phases of this project are presented. Industrial experience approach of geo-spot selection summarized from the interviews and theory study are presented. The proposed method of this project that is based on the industrial experience approach integrated with simulation solutions is concluded.

Industrial experience approach of geo-spot selection

To acquire industrial experience of the task, a comprehensive interview approach containing general questions, questionnaire, hypotheses, sketches and case discussions were applied to obtain both tacit and explicit knowledge of the interviewees (see Section 3.3). The interviewees were selected from the experts in the field of sheet metal assembly. The results from industrial experience of geo-spot selection are:

- The specific characteristics of geo-spots are used as the main criteria in the project (see Section 3.2);
- The verified hypotheses of geo-spots selection (see Section 4.1.2);
- Fifteen Consideration Factors (*CFs*) and four Classification Groups (*CGs*) of geo-spots selection are summarized (see Section 4.1.3);
- The *Root Cause Analysis* of these *CFs* and three main criteria (see Section 4.2.1)
- The importance-weights of all *CFs* are summed up to the priority list (see Section 4.2.2);
- An experience based workflow: Geo-Spot Selection Workflow (*GSSW*) mapping the above findings in a workflow is presented (see Section 4.2.3).

The proposed method of geo-spot selection

To support decision making in the process of geo-spot selection, the CAT-tool RD&T can be used to analyze and visualize the outcome of geo-spot selection. Therefore, the proposed method contains a Simulation Integrated – Geo-Spots Selection Workflow (*SI-GSSW*) that combines variation simulation with the experience base workflow - *GSSW*. Moreover, a decision making approach (AHP), that is utilized to evaluate the simulation results and decides the final selection of geo-spots, is also included in the proposed method. The results of the proposed method of geo-spots selection are:

- The proposed method is presented (see Chapter 5);
- *SI-GSSW* is established to fulfill the demand of industry (see Section 5.1);
- Four unique proposed simulation models are developed to support decision making (see Section 5.2);
- Decision AHP is investigated and utilized to find the best satisfied set of geo-spots (see Section 5.3).

Application of the proposed method to the Cases. The method is applied on two different industrial cases and the results are presented in Section 5.4. It is shown that the proposed method can satisfy the purpose of geo-spot selection and can be used to propose potential sets of geo-spots for further optimization.

7. DISCUSSION

In this chapter, the achievements and results of the thesis are discussed. Firstly, in this section the chosen methodology is commented. It states how the goals and objectives have been fulfilled. Moreover, it describes how this thesis contributes to the research that has been done in this field. Lastly, the future research possibilities are proposed.

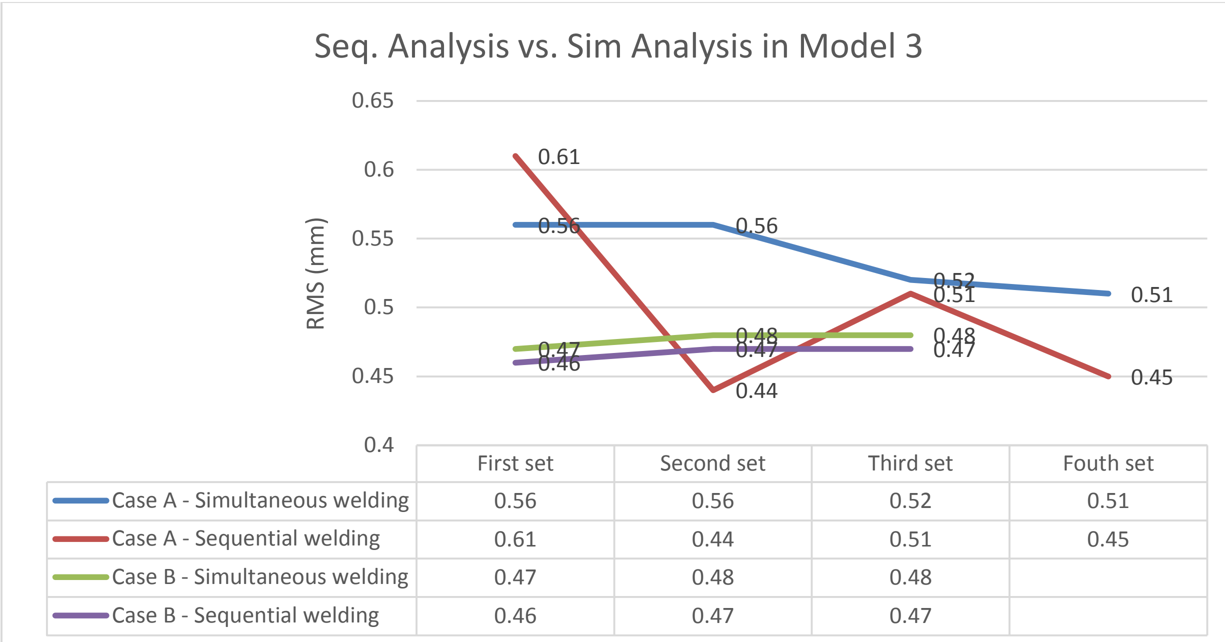
The methodology used in this project was inspired by the *Banks Simulation Methodology* that is a suitable method used for the computational simulation, while *Banks Simulation Methodology* needs to be refined to suite the actual project. In this project, the modified *Banks Simulation Methodology* has been proven to be easy to follow (see Section 3.1). Therefore, it is recommended by the authors of this report to adapt the *Banks Simulation Methodology*, based on the needs, in order to achieve the goals in a simulation project.

The goal of establishing a systematic method for geo-spot selection has been fulfilled by the new method composing of the *SI-GSSW* and the decision making approach AHP. Other than mapping the experience, the proposed method takes advantage of the simulations supported by the CAT-tool, RD&T (see Chapter 5). The applicability of the proposed method has been verified by applying it on the chosen case studies. The results achieved from the cases imply that the proposed method in this thesis establishes a standardized work procedure of the task of geo-spot selection (see Section 5.4).

While previous studies have investigated selection of important spot-welds in the sheet metal assembly, this thesis work presents three main criteria that specify the characteristics of the assembly after welding of the geo-spots. Fifteen *CFs* were identified and verified during the interviews of the experts within this field from VCC and some participants from Volvo Trucks (see Section 4.2.2). These *CFs* are connected to the main criteria which influence the geo-spot selection process. Based on the results achieved from simulations and after assuring that the proposed method is suitable for geo-spot selection, it can be stated that the chosen criteria and the identified *CFs* can be the basis of a standardized method for geo-spot selection in automotive industry.

The industrial cases in the study are provided by VCC and the simulation models were all built in the CAT-tool RD&T. By executing the variation simulation, the relations between geo-spots selection and assembly variation can be visualized earlier than verifying the assembly physically. The simulation results of selected geo-spots could have been further verified by the physical matching and trimming. However, the limited time for this project did not allow physical testing.

It is worth pointing out that sequence analysis of the selected set of geo-spot also has been conducted which supports the decision of selecting the best geo-spot set. As an effort to imitate the real production, different sequence trials have been executed in RD&T. For Case A, the results of the sequence simulation for the second and third set show that both sets have low part deviations, which is in line with the decision made by only considering the simultaneous welding of the geo-spots. Notably, it is discovered that on the second, third and fourth set the sequence models resulted in less deviation compared to simultaneous welding (see Figure 21, see Appendix C). Moreover, the sequence analysis of the selected set of geo-spots has also been executed for Case B. The outcomes of the sequence model in Case B show similar results for all the sets, the first set having the lowest RMS value of all models. However, the RMS values of sequence models in all sets are better than simultaneous welding by $0.01\,mm$ (see Figure 21, see Appendix C).



	First set	Second set	Third set	Fouth set
Case A - Simultaneous welding	0.56	0.56	0.52	0.51
Case A - Sequential welding	0.61	0.44	0.51	0.45
Case B - Simultaneous welding	0.47	0.48	0.48	
Case B - Sequential welding	0.46	0.47	0.47	

Figure 21: Seq. Analysis vs. Sim. Analysis

Therefore, the argument of previous research that the simultaneous welding will often result in less variation is not valid, when it is compared with the simulation results in this report [14, 4]. The findings of the sequence model prove that a well-chosen sequence of spot-welding might generate less mean deviation compared to the simultaneous welding [2].

The other aspect that has to be considered is that the differences between the results achieved by different simulation models are small (less than 1 mm). As it is mentioned, more investigations need to be made on the applicability of the proposed simulation integrated model, through implementing it to more assemblies. Due to specific process restrictions in the Case A and Case B, the chosen sets of geo-spots do not differ from each other to a large extent. Therefore, small differences are formed in the simulation results.

Finally, a general strategy for assigning the welding sequence for geo-spots could be investigated. More investigations are required to combine the proposed simulation models with welding sequence of geo-spots through applying GA method [2, 4]. It is also possible to develop more specific simulation models to meet the demand of industry. The simulation of non-rigid sheet metal assembly could be extended to multi-station assemblies in future research.

8. CONCLUSIONS

The purpose of this project is to investigate the current work procedure of selecting geo-spots in non-rigid sheet metal welding and develop a feasible method to increase the geometrical robustness and reduce the lead time for the task. To achieve that, a comprehensive workflow for identifying geo-spots in non-rigid sheet metal assembly is formulated and presented in this report. The workflow integrates industrial experience and simulation solution that is realized by RD&T software.

Moreover, a number of *CFs* influencing the decision of engineers in geo-spots selection are summarized and verified in the interviews. It can be concluded that *CF1 (Geometry specification)*, *CF2 (Type of part)* and *CF3 (Locating schemes)* within *CG1 (Design concept)* have the highest priority among other *CFs* (see Figure 16, Section 4.2.2). The *CG4 (Welding process restrictions)* has the lowest priority among four *CGs*. Engineers regard *CG4* as the pre-conditions of the process that cannot be changed in most cases (see Section 4.2.2).

Four simulation models are established to verify different demands in the process of selecting geo-spots. The results from the simulation models can assist the decision making of choosing suitable geo-spots on the assembly and visualize the consequences of an engineering decision. More importantly, the simulation models can transfer the work of physical trial to a virtual environment in RD&T. With the integration of simulation and industrial routines, the diagnosis of the geometry problems and error prediction can be conducted in earlier stages in the product development processes.

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APPENDICES

Appendix A: Interview data collection

A.1. Interview questionnaire

First Round- Warm-Up Questions

1- What data do you need in order to start with selection of the geo-spots? Is the model itself sufficient for this task?
   a. Important issues: cycle time, how to load the parts, locating scheme

2- How do you sort the respot points from those points for selection of the geometric points?
   a. Will you reduce the “must be taken” and “cannot be taken” points from the list initially?
   b. How to get information of hidden points?

3- What is your strategy for selection of the geo points?
   a. What do you expect for the outcome?
   b. Will you prefer to reduce the variations in all nodes after selecting each point?
   c. Will you usually start from one specific point to minimize the variations and consecutively optimize another point, one by one to the end?

Round 2- Influencing factors to the geo-spot selection task

4- Which factors do you consider are the most important when you choose geo spots based on the scenario of samples? Why?
   a. If you chose the points close to locators, why do you need the points as close as possible to the locators?
   b. In some situation, how do you make the balance of those factors?
   c. Does the situation that you have to change the selection of geo spots happen sometime due to some factors?

5- Will you consider the welding sequence when you sort out the geo spots?
   a. If you consider it, how does the welding sequence influence your decision?

   For example: will you consider the effect of the first selected geometric point on the other points? How the first selected geo points will affect the deviations in the other nodes?

   b. Will you generate different sets of welding points because of different sequences?

6- How many points do you think can secure the geometry of sub-assembly? (Show case A pillar)
   a. In general the way to select without knowing the locators…

7- Do you consider the effect of the welding force in your decision?
   a. Would you consider the one which needs more energy as a potential candidate for your selection / thin and thick parts?

8- How do you overcome the problems in the geometry during your test runs?
   a. Are there any routine methods for improvement after that you checked the results?
   b. For instance bumps between the sheets, or bends in the flanges

9- How difficult do you think the process of selecting geo spots is for amateurs?
   a. Do you find the process a time consuming task, overall?

A.2. Priority and evaluation table

Table 18: Priority and evaluation table

<table>
<tr><th rowspan="3">Classification Groups (CG)</th><th rowspan="3">Priority of Group</th><th rowspan="3">Priority of Factors</th><th rowspan="3">Consideration factors (CF)</th><th colspan="12">The relations between the selection criteria and consideration factors</th></tr>
<tr><th colspan="4">Criterion 1</th><th colspan="4">Criterion 2</th><th colspan="4">Criterion 3</th></tr>
<tr><th colspan="4">Assure geometry robustness</th><th colspan="4">Rigidity of parts withstand sub-assembly force</th><th colspan="4">Low influence of respot points</th></tr>
<tr><td rowspan="5">Design concepts</td><td rowspan="5"></td><td></td><td>Geometry specification</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Part thickness</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Locating scheme</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Type of part</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Number of parts</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td rowspan="3">Material Properties</td><td rowspan="3"></td><td></td><td>Spring back effects</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Part stiffness</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Material flow</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td rowspan="3">Welding Process parameters</td><td rowspan="3"></td><td></td><td>The amount of welding points</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Welding sequence</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Welding force</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td rowspan="4">Welding Process restrictions</td><td rowspan="4"></td><td></td><td>The geometry of welding gun</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Loading and processing sequence</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Fixture orientation</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td></td><td>Cycle time</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
</table>

*Please prioritize different classification groups in the Priority of Group column. The priority number starts from 1, which means that the group should be considered at the highest priority. Please prioritize each consideration factor within its group and give the number in the Priority of Factors column.

*Give weight of each consideration factor according to the relation with criteria 4 (strong), 3 (intermediate), 2 (weak), 1 (irrelevant) relation by choosing the number in the table)

*Please feel free to add any other element or cineraria that you find relevant in the blank rows and columns.

A.3. Hypotheses

The hypotheses of selecting geometry points are categorized into industrial solutions and theoretical logic.

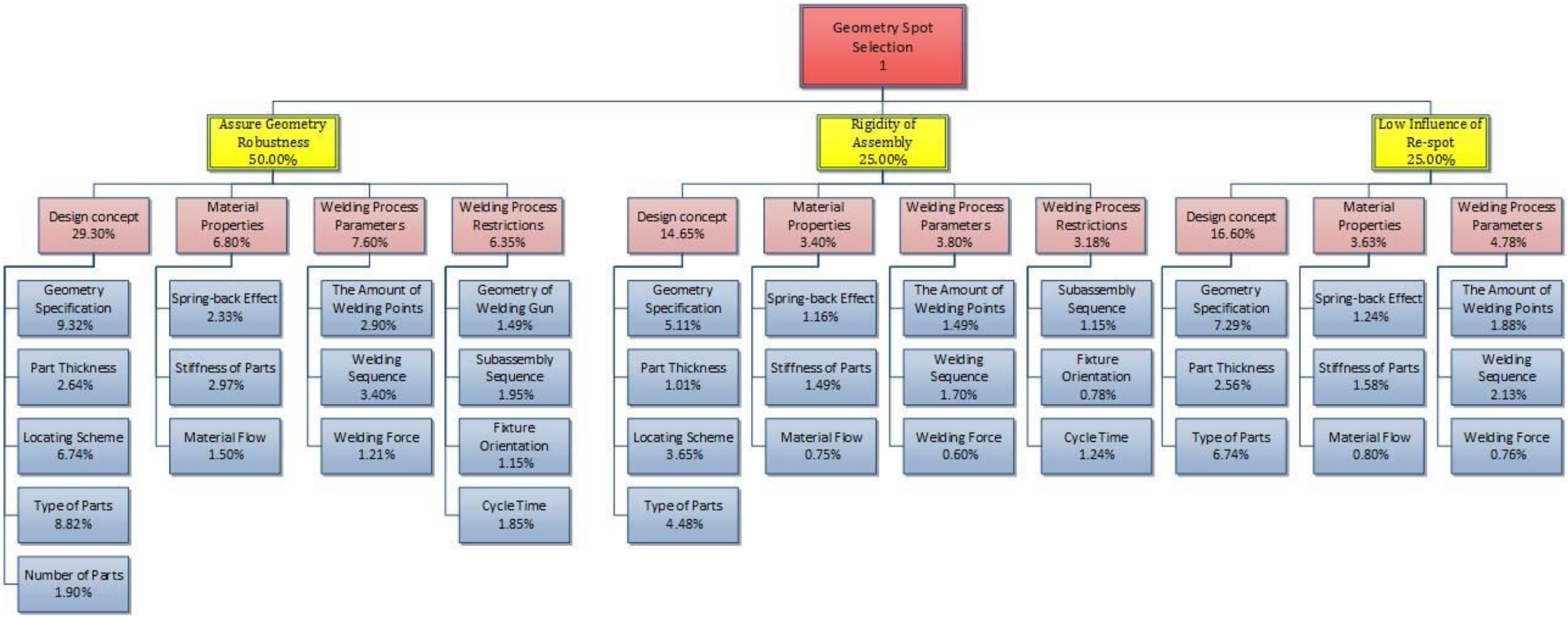
Should be geo spots

1. The welding points that are close to locators should be chosen firstly as geo spots.
2. The welding points that determine the geometrical requirement of part should be taken as geo spots.
3. The welding points that contribute to lock the main axis of the surface should be considered as geo spots.
4. The welding points should be as spread as possible to act as a part to part locating system to increase robustness, when the clamping system is restricted.
5. The selection of welding points should consider material thickness due to the fact that thick part has more influence on geometry compared to the thin part.
6. The welding points that have more effect on reducing the spring back effect should be selected as geo points.
7. When clamping points are on the both side of the sheets, and one of them are adjustable, the welding point that can flow the material the most should be selected as the geo point.

Should not be geo spots

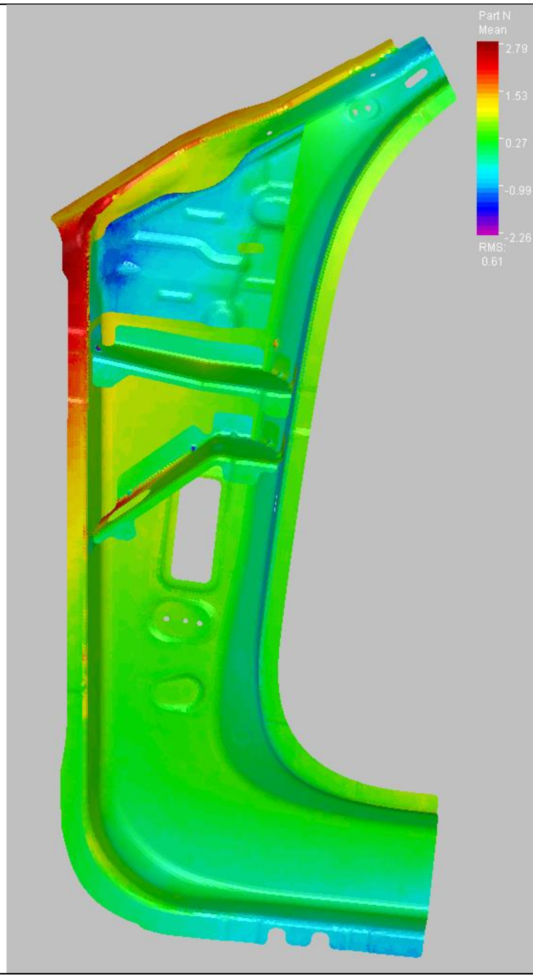
8. The welding points that are in conflict with geometry of the welding gun should not be taken as geo spots.
9. The welding points that are in conflict with reachability of the robot should not be taken as geo spots.
10. The welding points that are in conflict with assembly sequence should not be taken as geo spots.

Appendix B: AHP tree

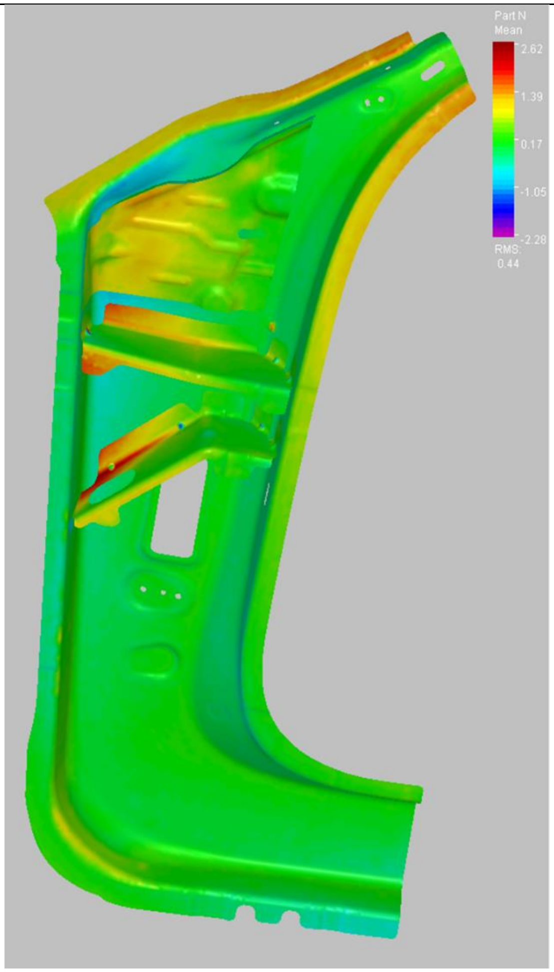


Appendix C: Sequence analysis results

Case A Sequence Analysis

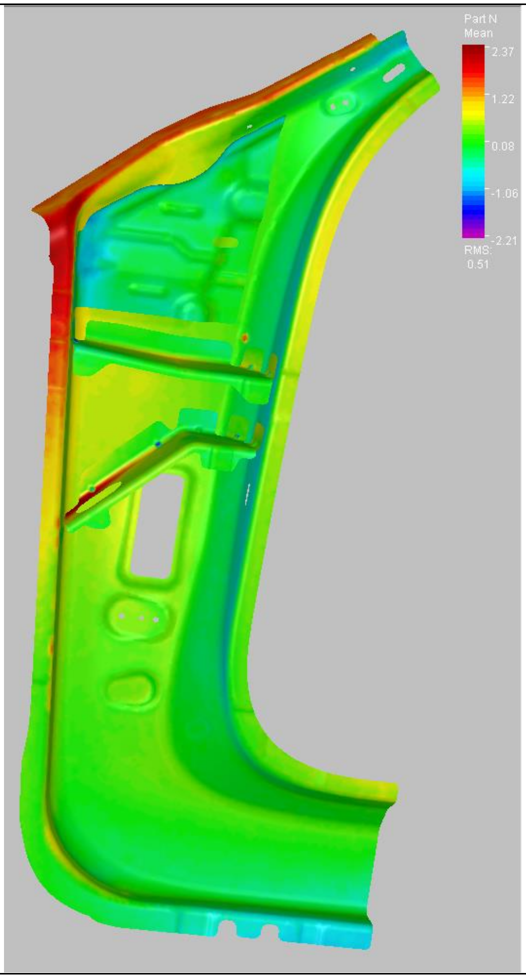
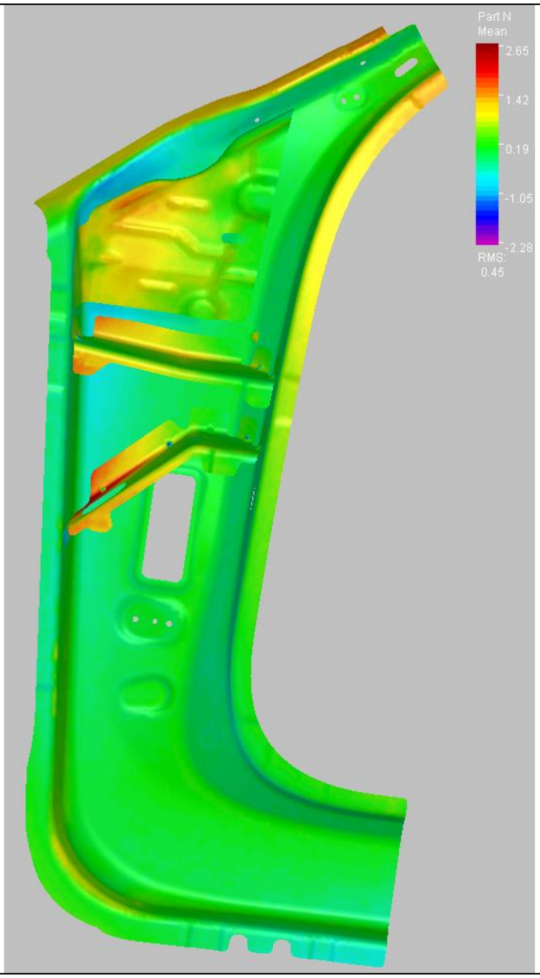


First set
Sequence of Geo-spots : {3, 4, 8, 9, 10, 12, 13, 14, 11, 1, 2, 5}
Mean Deviation Range: [-2.26, 2.79], RMS: 0.61

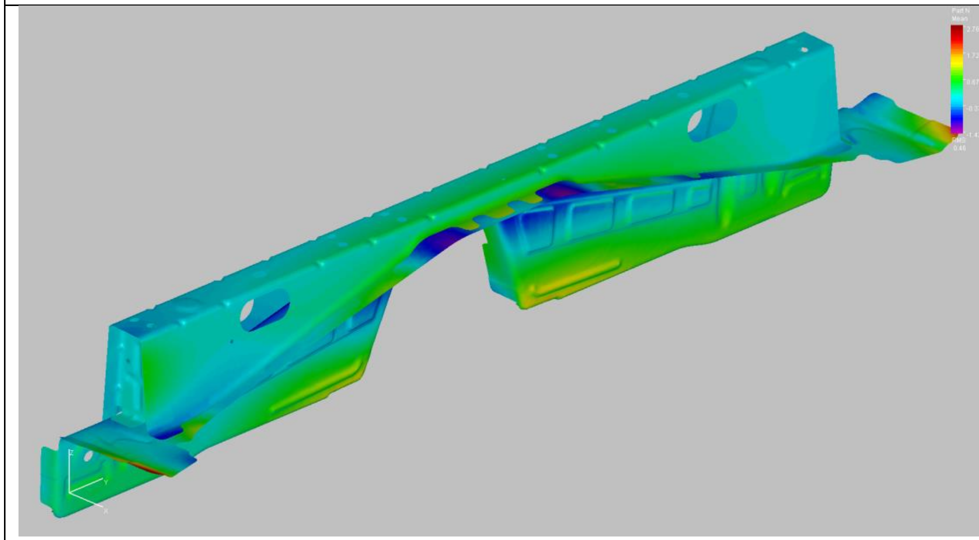
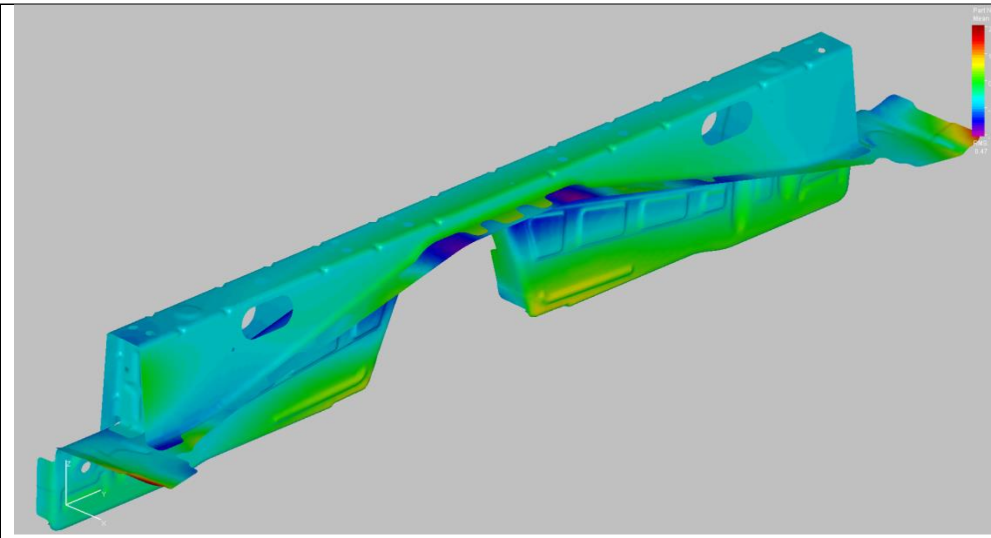


Second Set
Sequence of Geo-spots : {3, 8, 9, 10, 12, 13, 14, 11, 1, 2, 5, 6}
Mean Deviation Range: [-2.28, 2.62], RMS: 0.44

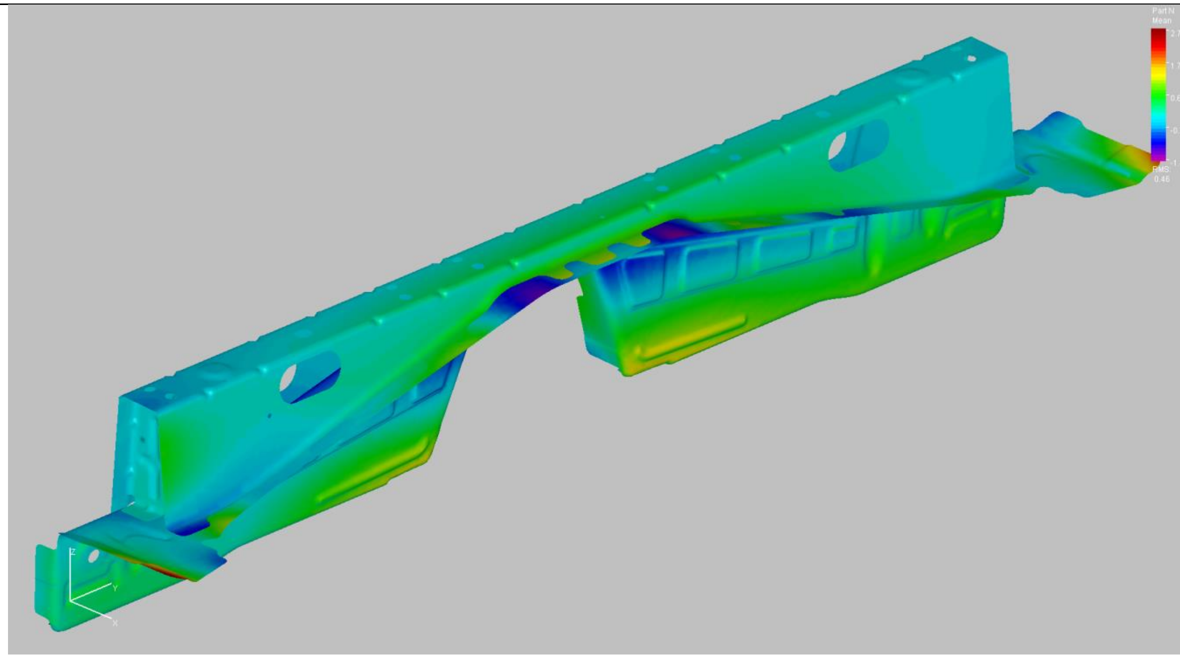
Case A Sequence Analysis

	
Third Set **Sequence of Geo-spots :** {3, 5, 8, 9, 10, 12, 13, 14, 11, 1, 2, 7} **Mean Deviation** Range: [-2.21, 2.37], RMS: 0.51	**Fourth set** **Sequence of Geo-spots :** {3, 5, 6, 8, 9, 10, 12, 13, 14, 11, 2, 7} **Mean Deviation** Range: [-2.28, 2.65], RMS: 0.45

Case B Sequence Analysis

	
First set **Sequence of Geo-spots :** {11, 13, 16, 19, 22, 24, 2, 3, 4, 6, 7, 8} **Mean Deviation** Range: [-1.42, 2.78], RMS: 0.46	**Second set** **Sequence of Geo-spots :** {25, 23, 22, 20, 15, 13, 12, 10, 9, 6, 4, 1} **Mean Deviation** Range: [-1.42, 2.93], RMS: 0.47

Case B Sequence Analysis



Third Set
Sequence of Geo-spots : {24, 23, 21, 18, 17, 14, 11, 8, 7, 5, 3, 2}
Mean Deviation Range: [-1.42, 2.79], RMS: 0.47

Appendix D: Interviewees List

Names	Company	Department
Magnus Andersson	Volvo Trucks	
Ola Carlsson	Volvo Cars	81250
Stefan Dahlström	Volvo Cars	93722
Josefin Hansen	Volvo Trucks	
Magnus Jakobsson	Volvo Cars	81250
Magnus Jivenfors	Volvo Cars	81250
Thomas Karlsson	Volvo Cars	81210
David Law	Volvo Trucks	
Lars Ljung	Volvo Cars	81210
Sievert Olofsson	Volvo Cars	81250
Mats Pettersson	Volvo Cars	81724
Francis Quaghebeur	Volvo Cars	E1260
Anders Rosenquist	Volvo Cars	81250
Lars Samuelsson	Volvo Cars	81722
Johan Segeborn	Volvo Cars	81620
Martin Swahn	Volvo Cars	93770