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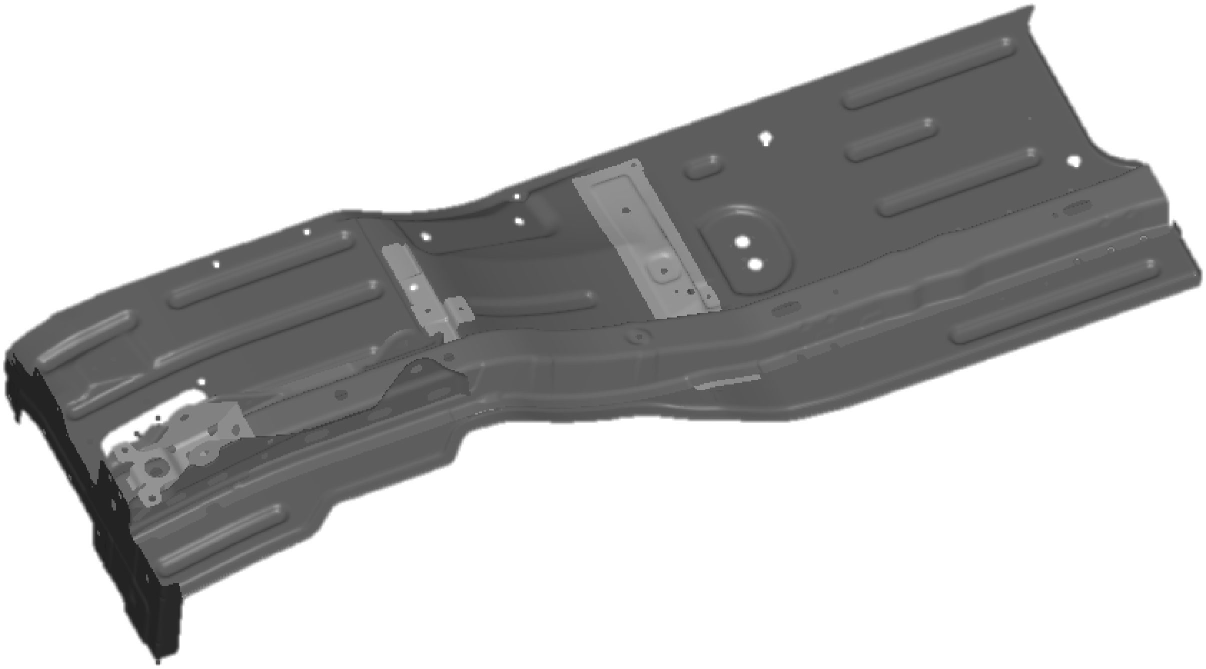

Sheet Metal Joining Process Parameters Evaluation in a Geometry Assurance Context

A Case Study at Volvo Trucks Technology & Volvo Trucks Operation

Master's Thesis in the Product Development

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DEPARTMENT OF Industrial and Materials Science
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Gothenburg, Sweden 2019

MASTER'S THESIS 2019

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Cover: The floor assembly case.

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ABSTRACT

The thesis was a master thesis project done at Volvo Trucks in cooperation between Technology and Operation departments with supervision from Wingquist Laboratory at Chalmers University in Sweden. During the assembly process of the sheet metals, a complicated combination of many assembly factors influences the geometry outcome and lead to unexpected deformation. The project is conducted in the geometry assurance field with the goals of evaluating the assembly process parameters and suggesting an improving method for the geometrical quality of the final assembly. The purposes are to highlight the most influential assembly factors and investigate the impact of changing the geometry spots (geo-spots) parameters on the assembly geometrical variation.

To achieve the project goals, directed interviews and surveys were made with industrial experts in Volvo Trucks Technology and Operation departments, to propose the most influential assembly factors that cause geometrical deformation in the assembly process, and to perceive and evaluate the approach of choosing the geo-spots parameters from experience perspective. Moreover, a study based on the Design of Experiments was performed to determinate the active geo-spots parameters. Furthermore, a sensitivity-based optimization for the geo-spots sequence was demonstrated and implemented to illustrate the ability for geometry improvement. Eventually, several variation simulations for different geo-spots parameters were executed for analysis and comparison purposes.

One industrial study case and three simple cases with common shapes were used to simulate, analyze and evaluate the gathered data. CAT simulation tool RD&T was used for the simulation and optimization purposes. The simulation results confirmed the survey results about the high variation sensitivity of the geo-spots position, number and sequence changes. It also showed that there is a big room for geometry improvement when implementing geo-spots sequence optimization. The DoE simulation results showed the number of geo-spots interacted with the welding sequence of the nearest locator and the welding based from the geometry spot to the nearest locator needs to be considered when deciding the location of the geo-spots.

The variation simulation results proved that using a variation simulation software significantly helps when choosing the most appropriate set of geo-spots parameters. Combining the CAT software simulation with practical engineering experience, improvement of the final assembly geometrical result could be achieved, and a more robust design could be made.

Keywords: spot welding simulation, geometry assurance, engineering improvement, operation analysis, DoE, CAT, RD&T

Acknowledgments

The project was carried out at Global Cap Technology Department, BF71110, at Volvo Group Truck Technology (GTT) and Trucks Operation (GTO) in collaboration with Wingquist Laboratory, the Chalmers University of Technology from January 2019 to August 2019. The supervisors of the thesis have been Timo Kero, Ph.D. Senior Technical Leader at GTT and Roham Sadeghi Tabar, a Ph.D. student at the Department of Industrial and Materials Science, Chalmers University of Technology. The examiner has been Kristina Wärmefjord, Associate Professor at the division of Product Development, Chalmers University of Technology.

A master thesis project is a special event concluding the education life. It is a realistic representation of the link between theory and practice. It is such a long journey full of learning, excitement, and fun with some stages of confusion and frustration. Luckily, the journey was finished, and the aims were achieved. We would not have finished what we started without the support and encouragement of those whom we would like to give them a great thanks and gratitude.

We would especially like to thank Timo Kero, our supportive supervisor who provided all the help, productive discussions and motivations, and guided us during the thesis to achieve our goals. Moreover, we would like to thank Roham Sadeghi Tabar, who was a great teacher and dedicated a lot of time and effort to pave the thesis path for us.

Also, a great thanks to Volvo Truck Operation for giving us the chance to visit the manufacturing area, gathering needed information and for their generous hospitality. We Would also thank Kristina Wärmefjord for her co-operation and valuable suggestions for the project, thanks to the Chalmers University of Technology, which provided such a great opportunity for us!

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Abdulwahab Dham & Xuewei Li, Göteborg August 2019

LIST OF ABBREVIATION

CAT	Computer-Aided Tolerancing
DoE	Design of Experiment
DoF	Degree of Freedom
DMC	Direct Monte Carlo
FEM	Finite Element Method
Geo-Spots	Geometry spots
GTO	Group Trucks Operation
GTT	Group Trucks Technology
HAZ	Heat-affected zone
MIC	Method of Influence Coefficient
RD&T	Robust Design & Tolerancing
RMS	Root Mean Square

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1. Introduction

This chapter provides the background, the aim of the project, and the target problem in the project. The limitations and research questions are presented. In the end, the outline of this master's thesis report is given.

1.1 Background

Volvo Trucks is one of the leading truck brands in the world, which has high quality and performance in all climates and working conditions [1]. In today's manufacturing industry, virtual tools and methods are becoming more important [2], to secure high-quality demands and robust designs from the market. Therefore, in the specific project, Volvo Trucks wants a possible solution that could evaluate the relevant parameters of the welding assembly process, meanwhile, improve the geometrical quality of the product and production development cycle to satisfy the market's demands.

At Volvo GTT (Group Trucks Technology), the Global Cab Platform group at the department of Cab Technology is responsible for developing the methods and processes for improving the results of Cab geometry. To ensure high quality and final robust design, virtual tools and techniques are being used during the concept phase, such as RD&T and other computer-aided tolerance tools (CAT)[2][3].

The Cab assembly consists of different rigid and non-rigid sheet metal parts. The typical joining process is spot welding especially when the assembly includes thin and flexible parts. The assembly process is considered as a very complicated process, where sequenced steps are executed, and different assembly parameters are set. Deciding how the parts are placed to each other (locating scheme) and how to hold the parts during the assembly process (fixturing) influence the assembly geometrical outcome. Moreover, choosing the positions, number and sequence of the first set of welding spots is a critical stage in order to assure a high geometrical quality of the final assembly.

As stated in [4], early verification in the early concept phase saves cost and time and the different welding sequences of geometry spots (geo-spots) could affect the final geometrical result [5][6]. Therefore, it is important to check and improve the effects of different welding sequences of geo-spots and support the decision making in the design phase for the target floor assembly.

1.2 Introduction of the geometry spots and re-spots

Spot welding is a common joining process in the automotive industry, where the production rate is considered as an essential factor. The followed method to keep the welding cycle time down is to divide the welding process into two main stages, the geometry spot stage and the re-spot stage.

The geo-spots are defined as the initial welding spots in a spot-welding process, the purpose of implementing the geo-spots is to secure the geometrical location of the sub-assembled parts. Geo-spots are usually chosen by industrial experience and they influence the generated geometry variation after welding[7].

Re-spots are defined as the remaining welding spots after finishing the geo-spot welding. The purpose of welding the re-spots is to strengthen the cohesion of the assembled parts, and re-spots have minimum influence on the geometrical outcome [7]. The re-spots can be set in any of the following stations after conducting the geo-spots to fit the capacity of the welding robots, and to create the balance between the assembly stations which ensure minimizing the cycle time [8].

In a conventional welding station, the followed procedure can be described as [9]:

1. Fixing the individual parts on the welding base.
2. Force the parts to its nominal positions and close the gaps by applying clamps.
3. Setting the welding spots.
4. Remove the clamps and release the new assembly to let it spring-back.

1.3 Aim

The project aims to find how the geo-spots are selected, what are the possible influential factors for the potential geometric problems and check the variation result of different sequences of welding geo-spots. Furthermore, making an improvement of the assembly process through early identification of the geometric problems. By investigating how these are handled, the study will have the following outcomes:

- Theoretical research about the spot welding process and to find the possible influential factors of geometrical quality by interviewing welding experts and engineers
- Make geometrical variation simulation to check the effect of different geo-spot sequences
- Suggest improvements to solve the geometric problems
- Provide a pre-study for the continuing project which includes more influential factors in the future

1.4 Limitations

The knowledge scope: Considering the limited time for the project and the limited knowledge scope of the thesis project workers, the team will mainly do the research from mechanical perspectives, which means that other areas, such as material science will not be included in the project.

The research scope: The research is also delimited to investigate the welding part in the geometry assurance context, focusing on the different sequences on the geometrical variation, but it could also be investigated in other contexts other than the geometry assurance context. For instance, a new investigation could be done in a new manufacturing process context to check if there is a better manufacturing process that could improve the geometrical quality of the target assembly.

The long-distance: Since the project needs a lot of data from the manufacturing department, which is in another city of Sweden, it was very hard to communicate and make a sufficient understanding of what the real situation is in the production line. Meanwhile, the laboratory availability for physical experiments was limited for the thesis workers. One note that needs to mention for preparing the modeling data is the feedback time for getting these data was too long due to the geographical problem and the corresponding engineers' schedule.

1.5 Specification of the issue under investigation.

The purpose of the thesis is to find the possible influential factors for the floor assembly geometrical problem and check the variation simulation results of different sequences of welding geo-spots and recommend improvements for the geometric problem. The sequence of the spot welds has a huge influence on the geometric results of the produced units [5][6]. Thus, a method to identify and evaluate the influencing joining parameters on the final geometrical outcome is looked for. In the project the following research questions are answered:

How can simulation support the early design phase, and improve the quality of the assembly to be jointed?

1. *How is the previous geo-spot sequence generated in the company?*
2. *What are the possible influential factors for the geometrical problem of the floor assembly?*
3. *What are the geometric variation simulation results of different geo-spot sequences?*

1.6 Outline of the report

Chapter 1 explains the background of the project, aim, research questions and limitations. Chapter 2 states the methodology applied in the project. Chapter 3 provides the theoretical background for the project and explains the necessary knowledge used in the project. Chapter 4 shows the results and analysis of interviews and the survey, which is the first practical step in the project. Chapter 5 is the design of experiment simulation section, which undertakes the results from Chapter 4. Chapter 6 explains the optimization simulation process of the target assembly, it shows how to generate the optimized sequence from the current welding spot locations. Chapter 7 is to analyze and compare the different simulation results from the previous chapters. After comparing all the simulation results, Chapter 8 draws a conclusion of the work tasks and provides possible recommendations for improving the results of the target assembly in the future.

2. Methodology

The methodology shows the procedures to finish each section in the project. In the following sections a thorough description of how the project was conducted will be presented. The four main sections and each step in these sections are explained as follows:

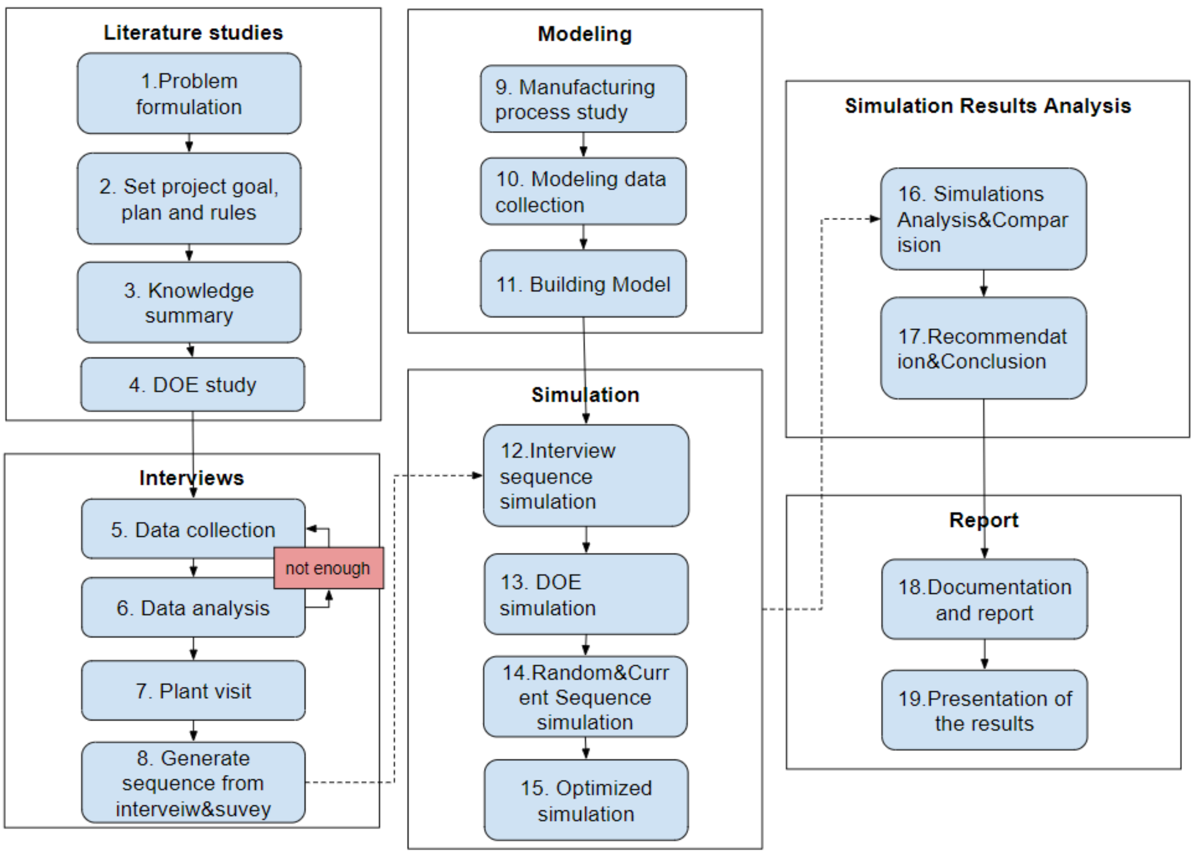


Figure 1: Project Methodology

2.1 Project Methodology Explanation

In this part, the main methodology and project procedures are explained in each sub-section.

2.1.1 Literature study

A literature review is first done to increase the understanding and knowledge of the theoretical part of the welding process. The general information regarding geometry assurance and manufacturing processes were studied as a start, serving as a base for the formulation of the interview questions and simulation part. The used articles were directly got from supervisors or discovered through the online library, using keywords such as *Spot Welding processes, Geometric Variation, Welding Simulation, and so forth.* Part of knowledge and ideas were also collected from other channels, such as internal meetings, research seminars, previous project experience.

2.1.2 Interview & Survey

Interviews were to be conducted, starting with an introductory interview with the welding engineers to find the answers about why they weld in a sequence, what kind of parameters they think are essential to be included in the simulation, etc. The interviews are semi-structured to enable more open and free answers from the interviewees. As mentioned by Hahn [10], a survey is a data collection tool by using different questions for getting a qualitative and quantitative result. There are different types of question applied in the survey, some questions are multiple-choice, fill-in questions, some questions are open-ended questions. The survey was designed to get the geo-spots selection result from the specific stakeholders, such as geometry engineers and manufacturing engineers. Meanwhile, practical visits were carried out in a manufacturing context in the company plant. By checking the real context other than just study on the theoretical level, the team got a real understanding of how the specified process is manufactured in the production line and find more details in the production context.

2.1.3 Modelling

The relevant data are collected at the host company for preparing the target assembly part modeling by using RD&T software [11]. A non-rigid variation simulation model is built to predict variation on assembly level and to investigate the effects of different spot welding sequences.

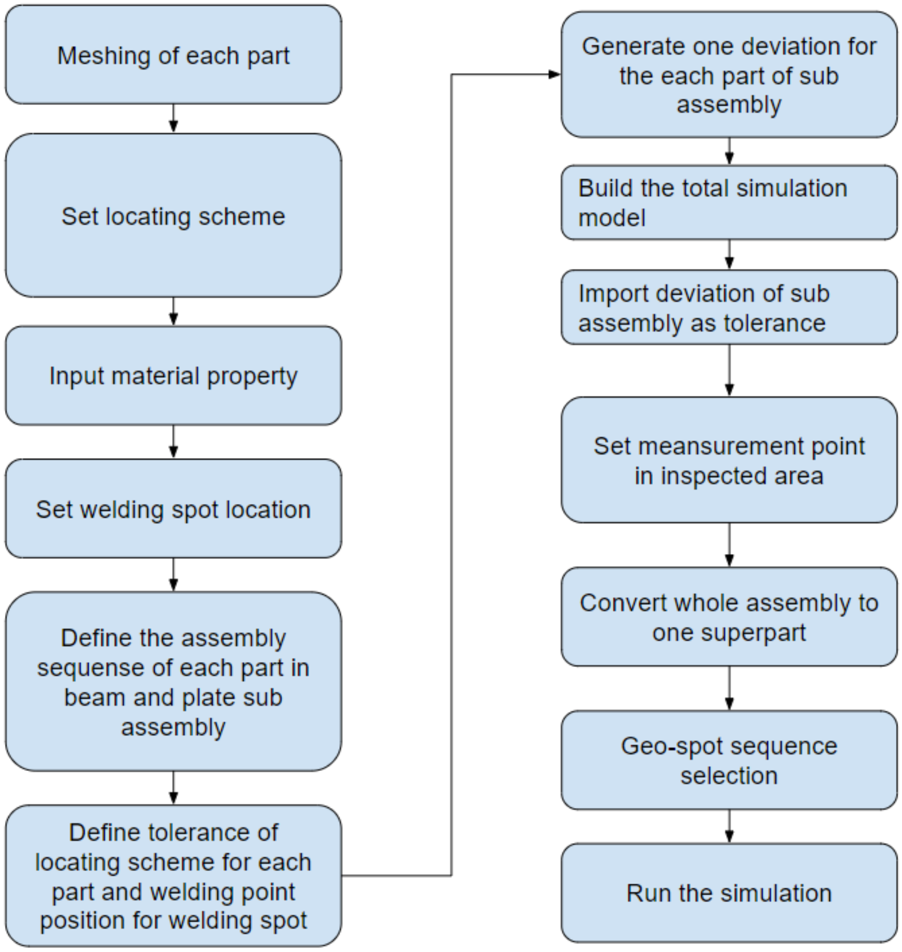


Figure 2: The process for modeling the sample assembly

Explanation of each step in the modeling process:

- The meshing parts: the individual parts of the beam sub-assembly and the individual parts of plate assembly are meshed as mid-surface shells with a specific size for the model by using ANSA pre-processor.
- Setting the locating scheme: to align and mate the parts and sub-assembly in its place, the positioning system were defined according to the manufacturing process.
- Input the material property: the major material property was obtained from the relevant department, and the thickness was checked from the part drawings
- Set welding spot location: Define the coordinate of welding spots both geo and re-spots as it is set by the assembly process.
- Define the assembly sequence: according to the assembly manual, which was received from the manufacturing department, the similar manufacturing process is defined for the modeling process
- Define the tolerance of locating scheme for each part: the tolerance of the sub-assembly parts was defined according to the company engineers
- Generate one deviation for the sub-assembly: One random geometrical deviation was

generated for each part within the allowed tolerances to represent as the nominal deviation of the part's geometry.

- Build the total simulation model: the complete assembly model was built after generating the deviation of the previous sub-assembly.
- Import deviation: the deviation generated from the sub-assembly was imported.
- Set measurement point in the inspected area: many measurement points were set at the mating surfaces to capture the geometrical changes and get the intended results.
- Convert the whole assembly to one super part: in order to reduce the size of the calculation matrix, whereas the original module consists of an enormous number of finite elements that make running simulation time-consuming.
- Geo-spot sequence selection: the geo-spot sequences were selected from the survey sequences, current sequence, random sequence, and optimized sequences, respectively.
- Run the simulation: different geo-spot sequences were generated, the geometric results of different welding sequences were compared and analyzed after running the simulation.

2.1.4 Report

By documenting the whole process of the project, the detailed information of simulation data, the working method, the survey results, and other relevant data were recorded and presented to the host company and the supervisors. The following chapters are to explain why the tasks are performed, what has been done for the task, and how the tasks were done.

2.1.5 Project procedure explanation

In the following sections, the detailed procedures are explained as shown in Figure 1.

1- **Problem formulation.** The project was aimed to handle the problem of cab floor plate-beam geometrical deformation, which is a critical problem that the host company works on solving it recently. The main task was to find the effects of different geo-spots sequences and improve the geometrical quality for the beam-plate floor assembly.

2- **Set project goals, rules, and plans.** The main goals are divided into different stages and transferred to a Gantt Chart. The project rules set up a team principal for the two project workers, which build up trust, working schedule, daily activity.

3- **Knowledge summary.** After finishing the literature review, the content of the reviewed papers is discussed within the team. Meanwhile, the possible solutions and relevant papers are shared with the engineers at the host company. There is an industrial need to develop a more advanced tool which could include more influential factors for non-nominal parts. It is understood that the current solution of the geo-spots' selection is made by the experience of the experts and not relied on scientific methodologies.

4- **Design of Experiments (DoE) study.** In order to make the DoE simulation, the DoE methods were reviewed. One DoE plan was made, and the feasible parameters are discussed with the stakeholders.

5- **Data collection.** The step was done by interviewing and survey with welding experts and relevant engineers in the design and manufacturing area. The interview questions are designed to get the reason for generating geo-spots selection for both general cases and the target assembly. Moreover, the possible influential factors are answered from their professional experience. A detailed explanation of the data collection methods is presented in the following pages.

6- **Data analysis.** After collecting the answers from the industry experts at the host company, the analysis was done by applying different analyzing tools for the interview and survey results. When there was no enough data for making the analysis, step 5 was repeated for collecting the necessary materials.

7- **Plant visit.** The manufacturing plant visit was scheduled in the project for having a floor assembly understanding in a production process environment. Meanwhile, interviews were done with the relevant engineers who are responsible for operating the floor assembly in the factory in order to have their experience and opinions for the research questions.

8- **Generate the sequence answers from interviews & survey.** Since the results from the interviews are very valuable, some welding sequences are generated from the survey under the help of experienced engineers.

9- **Manufacturing process study.** The manufacturing process of the target assembly part was studied and analyzed. After the study, the real production context in the plant was understood.

10- **The modeling data collection.** The relevant modeling data were collected for the simulation, which is mentioned in chapter 2.1.3.

11- **Building model.** After collecting the modeling data, the model of the target assembly part was built.

12- **Different welding sequences simulation from interview results.** As mentioned in step 8, the results of the geo-spots sequence generated from the interview will be used in this step. After running the simulation, the geometrical variation results were compared with other simulation results.

13- **Design of experiments.** DoE is described as a mathematical method that was used to learn how the uncertainty in the outcome of a mathematical model could be influenced by the different sources of its inputs. By inputting different values of the influential factors, the simulation results were generated and analyzed to check the effects of various parameters.

14- **Random & Current sequence simulation.** The random and current sequence simulations were done to get the geometrical variation results.

15- **Optimized sequence.** The optimized sequence of the geo-spots was generated by performing simulation-based optimization. The simulation models were built using the CAT-tool RD&T. The geometrical variation was obtained after running the optimized simulation, the total geometrical improvement was compared with the reference model.

16- **Simulations Analysis & Comparison.** Totally 5 simulations were analyzed and compared in this step. By analyzing the different results, some improvement could be found and generated.

17- **Conclusion & Recommendation.** In this chapter, some recommendations were given, and the conclusion was made. The recommendations and suggestions were collected from experienced engineers, supervisors, and summarized by the thesis workers.

18- **Documentation and report.** This step includes presenting the results and findings of the project.

19- **Presentation of the results.** The results achieved from the master thesis were presented at the host company and university, respectively, meanwhile, a scientific conference was taken as a pre-presentation for the project.

2.2 Empirical data collection

In this part, the methods applied in the interview and survey are explained in the following chapters.

2.2.1 General questions

The general questions in the survey are mainly two types, one is an open-ended question, and another is a closed-ended question. Due to the different potential parameters connected with the geometric problem, the relevant participants were chosen from different working areas, such as Design, Manufacturing or Material Department. Some of the participants were also recommended by the coordinator and supervisor at the company. The first part of the survey is to ask the participants to select the geo-spots of three typical cases. The second part of the survey is to find the participants' opinions about the floor assembly in the company. Due to the confidential problem, all relevant information about the floor assembly is not allowed to be presented in this report. The content of the general question could be checked in Appendix A.

2.2.2 General case model

The three different drawings were generated to visualize the different general cases, the precondition of these are explained at the beginning of the survey. The drawings are typical welding scenarios, which makes them easy to understand and easier to find general conclusions from the answers. The number, position, and sequence of geo-spots were asked in each case, which could summarize the commonality from their selected results. The content of the survey could be checked in Appendix B.

2.2.3 Different factors ranking

Different assembly deformation influential factors were presented for the participants to select. They were asked to rank the importance level of different factors from low to high. The reason to rank the different influential factors is to find and enhance the most important factors, which can be the reason behind the assembly deformation from the industrial perspective.

2.3 Optimization

In this part of the case study, a sensitivity-based algorithm is applied to propose the optimal sequence of nine geo-spots. The followed algorithm for welding sequences optimization is based on prioritizing the spot that has the lowest deviation influence on the geometry outcome of the assembly (lowest sensitivity). The best-proposed sequence by the followed algorithm is considered as a local optimum solution. The reason behind choosing the sensitivity-based algorithm is that it gives satisfactory results, besides the low number of simulation runs is needed compared to other types of the sequence optimization algorithm, that minimizing the optimization time which is considered as demand when simulating large and complicated models. The deviation simulation result of the current spot-welding sequence followed in the assembly process was used as a reference for evaluation and comparison. The deviation simulation result of the optimal sequence was obtained and compared to the current and random sequence results. Moreover, the improvement in implementing the optimal sequence was shown.

2.4 Case study

As mentioned in the previous section, three common cases and one target assembly part were presented in the survey.

2.4.1 Simple case models

The simple case models are presented in Chapter 4.2.1. The reason to select these models is due to their representative in the ordinary welding context. Observing the industrial method of selecting the geo-spots parameters and evaluating the geometry outcome of the final assembly using simulation software are needed to pave for the improvement. For example, Case 1 is a flat and cap sheet metals with two welded sides, case 2 is two L shaped sheet metals welded at the flanges, case 3 is a scenario where the weld points are locating on the curved surfaces. Shown in Figure 10. These three cases are presented as common welding cases and the sequence of welding is known to not influence the outcome.

The preconditions of all the three cases are the same: electrode force, weld current, weld time, electrode type and size, welding time between each spot, the distance between each welding spot in each case, applied material, the temperature. Each case consists of two non-nominal parts to be welded by spot welding, they are clamped by fixtures and has 2 mm tolerance for each part, questions were asked to:

- find strategies for selection these geo-spots
- find the commonality from the selected geo-spots
- find the most influential factors from their experience
- how to minimize the variation in the final assembly

2.4.2 Floor assembly scenario for simulation

The cab floor assembly shown in Figure 3, was chosen as a case study since it shows an unacceptable variation and mean-shift on the assembly level. The final assembly consists of many components passing through four main assembly stages during the manufacturing process. Therefore, many suspected factors associated with the component's geometry and the assembly process could stand behind the final geometrical deformation, and make it hard to be predicted in shape and value. The floor case study was included in the survey study to define and evaluate the influential assembly factors and the geo-spots parameters during the assembly process. It is also used as a simulation model to conduct DoE, to figure out the influence of changing the positions, number and sequence of welding spots on the geometry variation of the final assembly. Moreover, the floor case was used as a simulation model to conduct an optimization study to suggest the optimal geo-spots sequence. However, the reason for choosing the floor assembly case is to validate the simulation and optimization result however due to limitations the physical experiments were not performed.

The simulation model was built and performed using RD&T simulation software. The local deformation induced by the heat when adding the geo-spots can be neglected since the low spots number and widespread. In contrast, for the re-spots, the heat effect could highly influence the resulting deviation due to the large number and close location of the spots. Nonetheless, the heat simulation is not conducted for this thesis whereas the software capability to simulate the heat effect is under development

The cab floor assembly used in building the simulation model consists of the floor plate, the beam sub-assembly, and three reinforcement plats as shown in Figure 3, The main joining process is a spot welding where a predefined set of geo and re-spots fixes and strengthen the welded parts in its positions. The nominal geometries, material properties, clamping location, and positioning schemes of the parts and welding spots coordinates were taken from the industrial sources. Six locators and extra supporting points were implemented to lock and over-constrain the non-rigid parts in the space. One geometry deviation for each part was randomly generated within its allowed tolerances. More than 100 welding spots position were defined in the simulation model which made changing the geo-spots number location and position more flexible. The welding spots were set using a balanced welding gun and the contact model was included in order to take the surface collision into consideration when calculating the assembly deviation. Many measures were defined at the surfaces' contact in order to observe the normal displacement along the welding paths of the assembly, the value of the Root Mean Square (RMS) of all the measures was used for evaluation and comparison purposes.

Finally, in order to overcome the long simulation time since the model is computationally heavy, the model was reduced to its only measure points using special function in the RD&T simulation software.

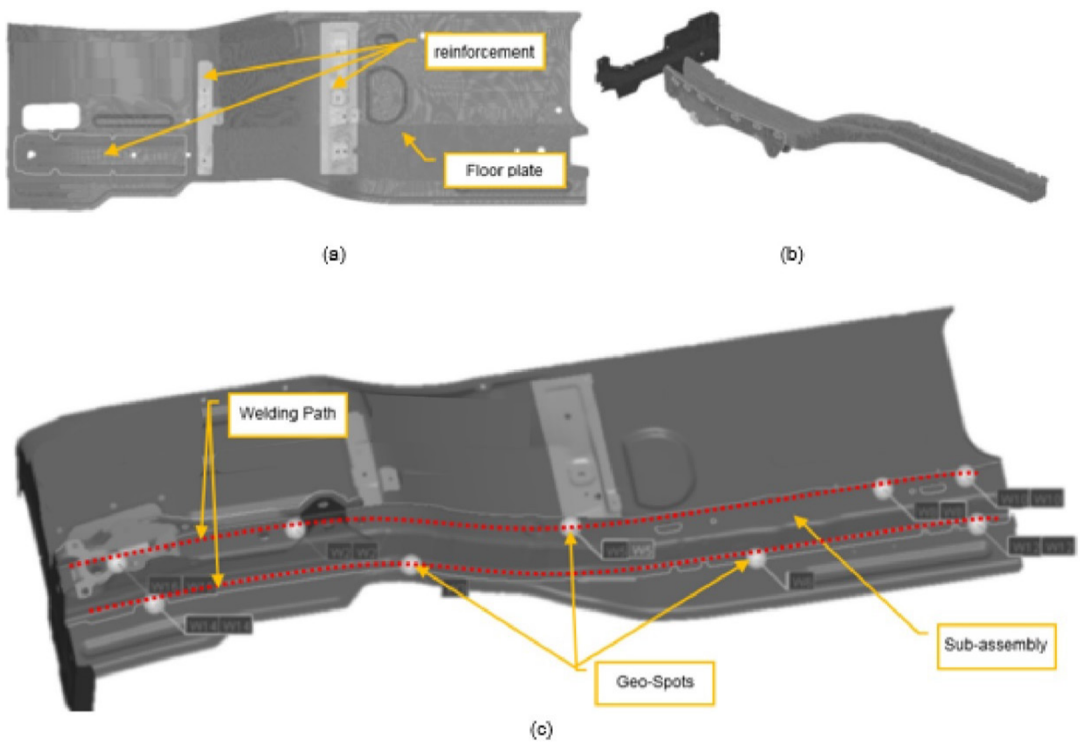


Figure 3: The floor assembly case, *W*here figure (a) shows the floor and reinforcement plates, figure (b) shows the sub-assembly and figure (c) shows the whole assembly with geo-spots and the welding path.

The assembly scenario is shown in Figure 4 to give an assumed process for the CAT simulation.

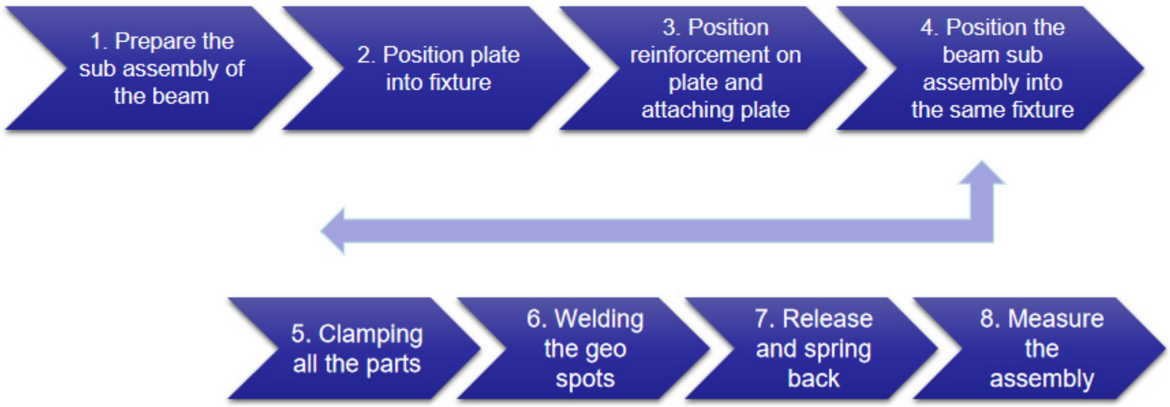


Figure 4: the assembly process for the simulation

2.5 Design of Experiments

The Design of Experiments (DoE) was applied in the project for checking the effect of different parameters. DoE is a statistical technique to find the effect of several process parameters that affect the final response of a product. The reason to use the DoE method is to identify the critical parameters of the target floor assembly. It is an advanced method that applied in the improvement process of Six Sigma for improving stability, process outcome and reduces variability. Three potential parameters were chosen and a 2^3 full factorial design in the project, since all possible interacted effects need to be investigated in the project. The procedures are explained in Chapter 5.1.

3. Theory and literature review

Geometrical variation in manufacturing and assembly processes could affect the product quality and could influence the functional, esthetical, or assembly requirements. Commonly, the geometrical quality problems that discovered late with a huge fixing cost can be avoided in the early phase [12]. According to [4], around 60% of late changes in new product development relates to unclear concepts or tolerances. Moreover, the changing cost would be quite extensive and complex for the stakeholders. The geometry related issues play an important role in the product lifecycle and should be considered in advance.

3.1 Geometry Assurance

Geometry assurance could be understood as the activities that contribute to minimizing the geometrical variation effect for the final product [12], throughout the product development process as shown in Figure 5 [7]. As Söderberg et al. [12] mentioned, an effective geometry assurance process is essential and benefit for both design and production phases, such as reducing cost and adjustments, shorten locators' definition time, etc. Geometric problems can be found in all the different phases of the product realization loop, which are concept phase, verification phase and production phase [12].

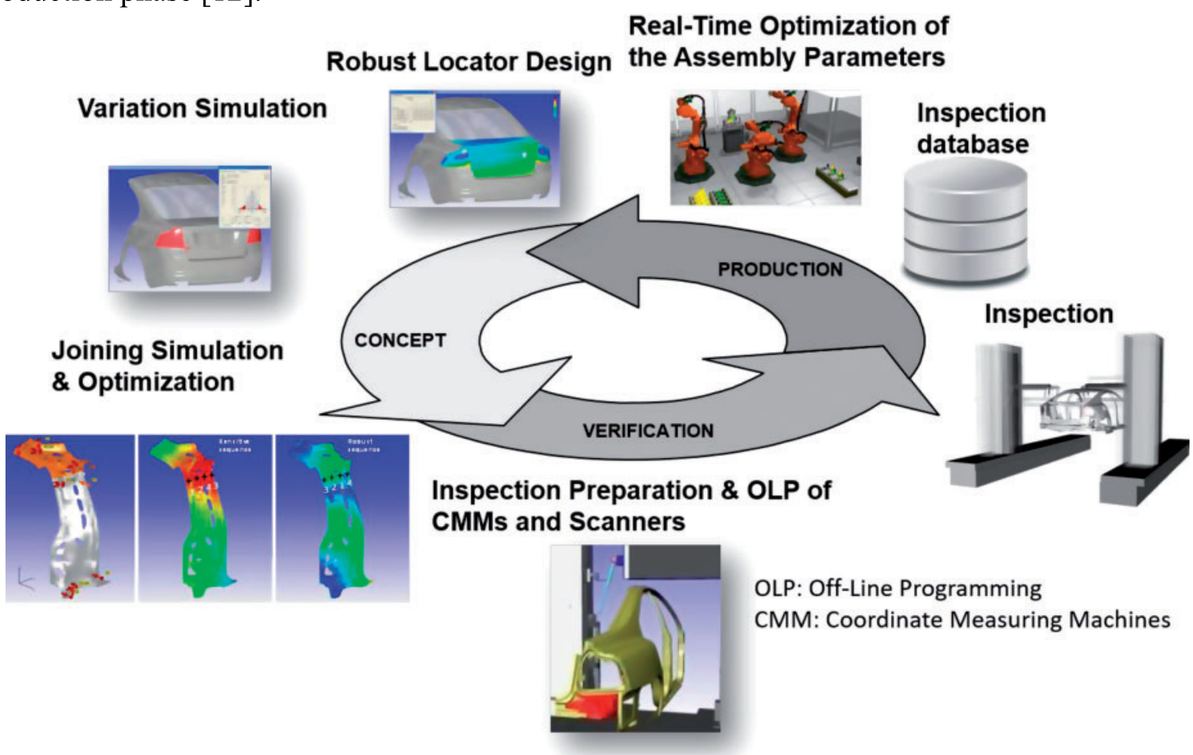


Figure 5: Virtual geometry assurance activities [7]

Different concepts are proposed in the early concept phase. Variation simulation tools are used to evaluate, compare, and select the most robust design concept. Moreover, finding the optimal locating schemes, that allocate the position of the parts during the assembly process, is a critical process to minimize the propagation of part variation to the assembly variation level. In this stage, the tolerances are assigned also to control the assembly geometric variation in order to keep it within the allowed limits and fulfill the aesthetical and functional requirements [13].

3.2 Spot welding process

The spot welding process is a typical joining process in the automotive industry. In this process, the two contacting metal surfaces are joined by heat generated once the welding current is applied [14]. Through this process, two electrodes are used to clamp the metal sheets together and transfer the welding current. As the welding current goes through the sheets interfaces a molten pool (weld bead) is generated by the heat at the joint interface because of the high resistance [14]. After the welding current is stopped, the molten pool solidifies and produces a weld nugget. The advantage for the spot welding is that a lot of energy can be transferred to a small spot in a short time (from

10 to 100 milliseconds), meanwhile without harming the rest of the sheet. As stated by Wärmefjord et al.[5], the result of it might be influenced by variations from various causes, such as the welding gun, the generated heat, the fixture variation, etc. Therefore, the relevant parameters are explained in Chapter 3.3.

3.3 The different influential factors for assembly

There are many possible factors that could affect the assembly variation and lead to a mean shift from the nominal values. Some of these factors are explained below:

3.3.1 Part variation effect

In the parts manufacturing process, parts are produced with non-nominal geometry dimensions (geometry variation) due to the machines, tools, and process precision besides the variation of material properties. This geometrical variation is usually shown as geometrical tolerances and inspected data to make a good prediction for its influence on the assembly variation.
Hu and Liu state that the assembly variation is influenced by thicker part variation more than a thinner one, for the same material properties [9].

3.3.2 Fixturing effect

The fixturing process has a significant influence on assembly variation. It includes positioning and clamping of the assembly's parts. The positioning step is to locate the unwelded parts according to a predefined locating scheme and lock the 6 Degrees of Freedom (DoF), which fix the parts in the space and prevent the six rotation and translation movements. Clamping is applying forces on the non-nominal parts to ensure the surface alignment and mating, and to hold them during the assembly process. Choosing an appropriate locating scheme minimizes the sensitivity to the parts variation and controls the assembly robustness. Moreover, applying the inappropriate clamping forces may cause different issues like plastic deformation when applied too high forces, or fail joints when applied too low clamping forces. Besides that, the sequence of clamping has its own effect on the assembly variation. Camelio and Hu showed how the assembly variation is affected by the fixture design and applied optimization method to find the optimal fixture position [15].

3.3.3 Joining process effect

Joining parts is the main process for the assembly production that has many parameters with significant impacts on assembly variation. The spot welding process is a fully automated process and highly controlled with low cost, which makes it widely used in the automotive industry. Choosing the spots' location, number, and sequence controls the assembly robustness and variation. The excessive closure force applied by welding gun jaws can displace the joint from its nominal location and cause geometrical deformation for the welded products.

3.3.3.1 Geometry points effect

The number and location of the welding points determine the assembly strength while the first few welding points in a welding sequence determine the assembly geometry variation. Those few first welding points that lock the assembly geometry in the 6 DoF are set in a sequence and called geometry points. The remaining welding spots that have a minimal effect on the assembly variations are responsible for the assembly strength, those spots are called re-spots and set with respect to cycle time [16]. For efficient production cycle time with respect to geometry assurance, the geo-spots and re-spots welds are executed in different stages. Therefore, focusing on the geometry points number, location and sequence is essential to achieve high geometry accuracy and minimize the assembly deviation. To confirm the good choice of geo-spots three criteria were set [5]:

Criterion 1: ensure geometry robustness and product functions.
Criterion 2: ensure rigidity of parts to withstand forces.
Criterion 3: minimize the geometric influence of re-spots.

3.3.3.2 Welding sequence effect

Setting the geometry points is usually done in a sequence and takes into consideration the cycle time. Changing this sequence causes changes in the final assembly variation. Defining the best welding sequence is a big challenge since no linear relationship between the sequences and assembly variation exist, besides a large number of the potential sequences can be applied to a few numbers of welds, for example, ten weld points have 10! = 3.6 million alternatives.

No much research has been conducted to propose the optimal spot weld sequence. Some of them suggested a generic design criterion for non-rigid bodies welding sequence, suggesting the optimal sequence depends on the minimum stress accumulation during the welding process which in turn relates to the geometrical variation [17]. Other research introduced a selection method based on a systematic search algorithm in the quality context [18]. More work has been done in the optimization area based on genetic algorithms [19] to propose the optimal number, positions, and sequences of the weld spots and welding cycle time, where an objective function is defined to get the lowest value of deviation or variation of predefined dimensional measures [20] [21]. Evaluation and comparison of the performance of three different optimization algorithms for finding optimal sequences were conducted [22]. Tabar et al. have introduced methods for the identification of geometry weld points and sequence optimization [7]. A novel rule-based approach has also been introduced for spot welding sequence optimization for the individualized assembly lines [23].

3.3.4 Heat effect

The heat generated during the welding process considers as a reason for local distortion in the welding spot area. During setting many spots these local distortions accumulate to contribute the geometrical deformation of the whole assembly. The reasons behind this distortion are derived from [24][25] and concluded as:

- The metallurgical changes in material structure at the welding bead and the heat-affected zone (HAZ): The metal melts and solidifies at the bead, and the metallurgical phases in the HAZ changes, that generate material shrinkage induced as a geometrical distortion.

- The material thermal expansion and contraction: The physical phenomena of the volume changes of the material when the material temperature changes might cause shape deformation, that happens when the shape expands under fixture so the expansion value will not be uniformed in all the direction, and after the contraction the welded product might not be able to retrieve its original shape.

- The changes in the mechanical properties at the welding spots: as mentioned before the material's phases structure at the bead and HAZ changes which in turn causes changes in the mechanical properties like the strength, ductility, hardness, etc. So the area that elastically deformed under jaws forces of the welding gun will not partly retrieve its original shape after the mechanical properties changes (plastic deformation).

Many welding spots are set during the re-spots stage in the assembly process that makes the need for taking the heat effect into consideration is essential to ensure high geometrical quality.

3.3.5 Other factors

Other factors that have non-negligible influences should be considered for obtaining better geometry outcome. Such as the gravity effect on large and heavy parts, and the joining and fixture tool wearing that lead to diversity in assembly variation during production. The collision between the parts during the assembly process generates forces, which in turn considered as a deviation source, the contact model was developed and implemented in simulation software RD&T to calculate the collision deviation [26].

3.4 Non-rigid variation simulation

During the assembly process of the sheet metals, a geometrical deformation can occur because of the non-rigid behavior under applied assembly forces. Include the deformation analysis in the geometry variation simulation of a non-rigid assembly gives more realistic results. That is achieved by combining The Finite Element Method (FEM) with the traditional variation simulation methods. Two improved approaches were developed to simulate a realistic assembly variation, which are Direct Monte Carlo (DMC) and Method of Influence Coefficient (MIC). Both methods give accurate variation distribution, but DMC is characterized by time-consuming where two FEM simulation runs are performed for each iteration. Since variation simulation analysis is a statistical study, many of calculation iterations should be conducted, that delimits using DMC for simulating complex assemblies. In contrast, the influence coefficients method depends on a derived linear relationship to minimize the computing time, which makes this method more efficient and applicable for variation simulation of non-rigid assembly [9].

In order to find the geometry variation in an assembly, the function ($\boldsymbol{f}$) which defines the assembly deviation ($\boldsymbol{x}$) according to the part deviations (y_i) is described below:

$$\boldsymbol{x} = f(y_1, y_2, \ldots., y_n)$$

Function ($\boldsymbol{f}$) is usually determined by only geometrical/kinematical relation when simulating the variation of rigid parts assembly; mechanical relation is mainly involved when assembling deformable parts. This mechanical relation defines the interaction among non-rigid parts during the assembly process.

The assembly process of sheet metal is usually done through four main steps, these steps define the mechanical interaction which illustrated in Figure 6 and explained as below:

1. Positioning unwelded sheet metal parts in assembly fixture according to predefined locators.
2. Forcing the parts to its nominal positions by fixture clamps and welding gun jaws.
3. Joining the sheet metal parts.
4. Releasing the welded parts from the clamps.

Stacking up the combination of geometry variation (input) introduced by different sources such as parts, fixtures, clamps, and joining tools in the assembly process causes the geometry variation (output) of the assembly. If appropriate clamping and tools are used in the welding process, the geometrical deviation of the parts is considered as the main source for the assembly deviation.

Using the finite element method means to divide the parts into a number of small elements joined by nodes. The deviation of each node from its nominal position represents local deviation (v_i), and the vector of local deviations represents the total part deviation $\{V_u\}$. Parts deviations are shown when unwelded parts are positioned in the assembly fixture in step one. During step two, assemble clamps and welding gun jaws force the parts to its nominal position by applying forces represented in vector $\{F_u\}$, where these forces displace each node by the magnitude $\{V_u\}$.

$$\{F_u\} = [K_u]\{V_u\} \qquad (1)$$

Where $[K_u]$ is the stiffness matrix of the part which is generated in FEM simulation software internally and related to the part mechanical structure.

In step 3, the joining process is performed, and the sheet metal parts become one assembly that consists of a number of nodes in the FE model. The mechanical behavior of the total assembly is represented by the assembly stiffness matrix $[K_w]$ which also calculated by FEM software internally.

In Step 4, when the assembly is released, and the clamps are removed, the forces that were applied are eliminated which allows the assembly to spring back and deviate from the nominal geometry. Formulation (2) calculate the spring-back for total assembly represented as a vector of deviation of each node:

$$[K_w]\{U_w\} = \{F_w\} \rightarrow \{U_w\} = [K_w]^{-1}\{F_w\} \quad (2)$$

Since the forces applied to the unwelded parts $\{F_u\}$ are the same forces that applied to the welded structure $\{F_w\}$, that enables building a mathematical formulation to calculate the assembly deviation depending on the parts deviations.

$$\{F_u\} = \{F_w\} \quad (3)$$

To execute the statistical analyses for geometry variation thousands of runs are needed, when the deviations of unwelded parts are provided as a range of tolerances. For each run, two FEM calculations are executed, which makes the DMC method time-consuming and not feasible for large and complicated models even if using super performance computers.

In order to make the statistical simulation feasible, there is a need to significantly decrease the computing time of FEM. Depending on equation (3):

$$[K_w]\{U_w\} = [K_u]\{V_u\} \quad (4)$$

$$\{U_w\} = [K_w]^{-1}[K_u]\{V_u\} = [S_{wu}]\{V_u\} \quad (5)$$

Where $[S_{wu}]$ called the sensitivity matrix and represents the linear relationship between unwelded parts deviations and assembly deviation. In this case, just two FEM calculations are needed to build the sensitivity matrix which extremely reduces the computational time. This method is called the Method of Influence Coefficient [9].

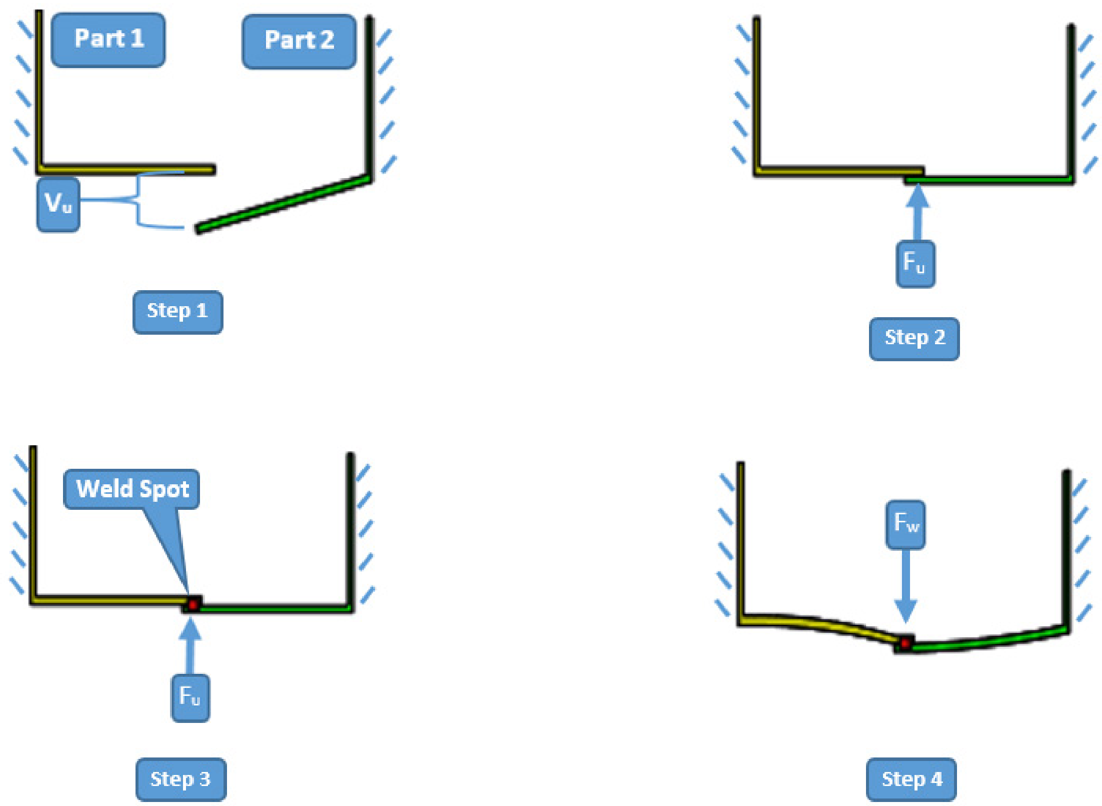


Figure 6: The four main steps assembly process of sheet metal

The local distortion induced by heat and welding jaws force at the welded nugget is neglected. Moreover, the previous calculation method is appropriate for the simultaneous welding process simulation. Including a joining sequence in the variation simulation of non-rigid parts can be done by using the previous simulation method (Monte Carlo method) with more complexity. The gaps between the parts are closed in sequence according to the welding sequence, whereas each welding sequence has its different gaps closure, which in turn has a different final spring back result.

To simply clarify the variation simulation process with a joining sequence, the previous four steps of the assembly process of sheet metal are iterated when each joint is added one by one. At the end of each iteration, the spring back of welded assembly is calculated which means calculate the changes in the magnitude of the gaps, applied clamping forces, raised forces and penetration status between the mating surfaces. The updated assembly stiffness matrix for simulation after adding a new joint is used for performing the calculation when the next joint is set [5]. Once all the welding joints are added, the clamps are released allowing the final assembly to deform in its targeting fixture, the total spring back (assembly deviation) and joining forces are calculated in each MC replication[5].

Performing variation simulation for models with large size and big numbers of welding spots is still time-consuming even if MIC is used. However, a new efficient method was recently proposed for variation simulation of non-rigid assemblies, which can save computing time up to 50% compared to the used methods [27].

4. Interview & Survey Results and Analysis

In order to get a deeper understanding of the geo-spots welding process, semi-structured interviews were made with experienced engineers. The purpose of interviewing experts is to learn more about the manufacturing details in the floor assembly context, the most possible influential factors in their mind, how and why the geo-spots were selected, etc. Since some of the interviewees have been working in the welding area for more than twenty years, the outcome of the interviews is valuable and productive. Eight face-to-face interviews of one to two hours have been conducted at the R&D and manufacturing department respectively.

The content of all the interviews was documented by minuting and audio recording, which was later used to make transcriptions for the data analysis. The strategy for the interview was to find the main questions' answers from the interviewees and provide free time for them to show their understanding and insight about the geo-spots manufacturing issues. In this way, more details would be shown up from them.

The data were collected to identify customer needs using qualitative and quantitative methods such as interviews and a survey. Geometry and welding expert interviews are conducted for getting more detailed information about the design and manufacturing processes. The interviews were done at Volvo GTT (Group Trucks Technology) and GTO (Group Trucks Operation) respectively. The data of the survey were collected and analyzed to find how the previous geo-spots were selected, what were the reasons for these geo-spot selections etc. A more detailed description of how the methods were used and what outcome they provided is presented within the following sections.

The selection of the geo-spots was normally done by the geometry and manufacturing engineers within different functional departments. As so, in order to have the reason behind the previous geo-spot selection, some interviews are done with the relevant engineers from different departments. The interviewees were selected in the following order based on their functional roles, some interviewees were recommended by the company's coordinator:

From Volvo Trucks Technology;

1. *Geometry Engineers: two engineers*
2. *Manufacturing Engineering BIW: one engineer*
3. *CAE Engineer: one engineer*

From Volvo Trucks Operation;

1. *Manufacturing Engineering BIW: one engineer*

2. *Geometry Engineer: one engineer*
3. *Production Engineering: one engineer*
4. *Welding Expert: one engineer*

4.1 Interviews results & analysis

The interview consists of mainly two parts: the first part is to get the answer to general questions from the engineers, the second part is to ask specific questions in their working area about the geometrical deformation problem. After gathering all the opinions from the engineers, an interview summary was made for describing all the collected opinions.

I. General questions

1. ***How do you decide the sequence, number, and position of spot welding?***

It is understood that the sequence, number, and position of geo-spot is decided by the geometry technician's experience at the company. According to their answers, the geo-spot selection method depends on different parts, which means a different shape has a different geo-spot selection method, sometimes it can be changed according to a different manufacturing process.

2. ***What are the possible influential factors that affect the final assembly?***

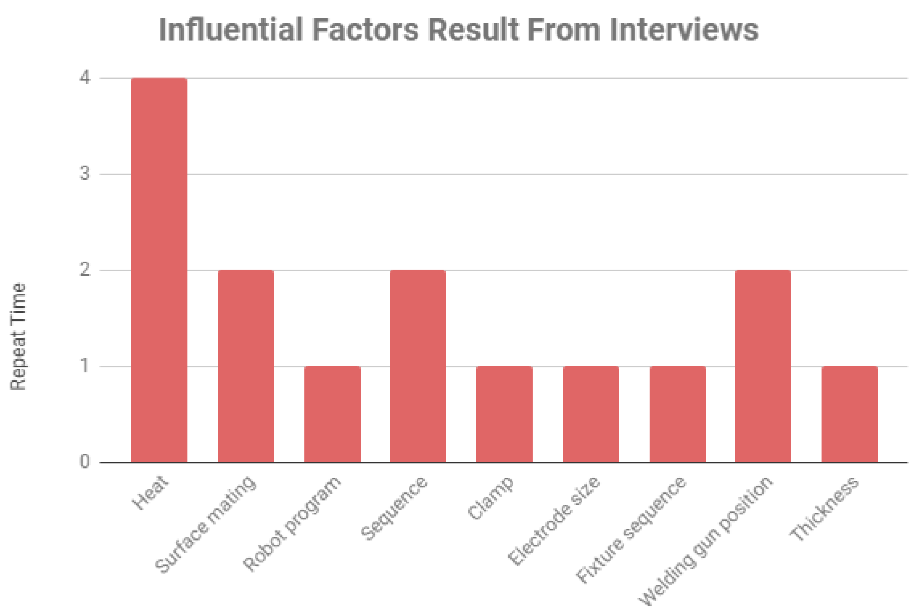


Figure 7: Influential Factors Result from Interviews

When asked about the possible influential factors for the final assembly, the answers were varied. It could be found in Figure 7 that the 'Heat' factor has the highest repeat time and the 'Sequence' factor, 'Surface mating' factor and the 'Welding gun position' factor has the second-highest repeat time. The top four most frequent factors will be explained in the following.

- Heat: As understood from the engineers' answers, the heat could change the property of the material when spot welding the parts. The high temperature could expand the material shape. Another reason for generating the heat is from the number of welding spots, after the geo-spot welding, a lot of re-spots are welded in the next station, thus more heat will be generated from the re-spots welding since few geo-spots are set. Moreover, the distance between re-spots is shorter than the distance between geo-spot, which means re-spots welding has higher heat per unit area.

- Surface mating of the welding parts: As the engineers mentioned in the interviews, there will be some gaps generated if the assembled parts are not matched with each other, it could be due to the fixture accuracy problem, it could be the part variation problem, it could also be other problems.

- Sequence: As explained in the literature review chapter, different sequences have different variation results, the more geo-spots have, the more possible sequence alternatives will be generated. Since there are 9 geo-spots in the assembly, the possible sequence will be more than 36000 possibilities.

- Welding gun position: According to the welding expert and the senior engineer, it is very hard to synchronize the robot with the welding sheet in the production line, it means there could be some variation from the welding gun position.

After the interview with the experienced engineers, the team analyzed and summarized the influential factors for the target assembly as it is shown in Figure 8:

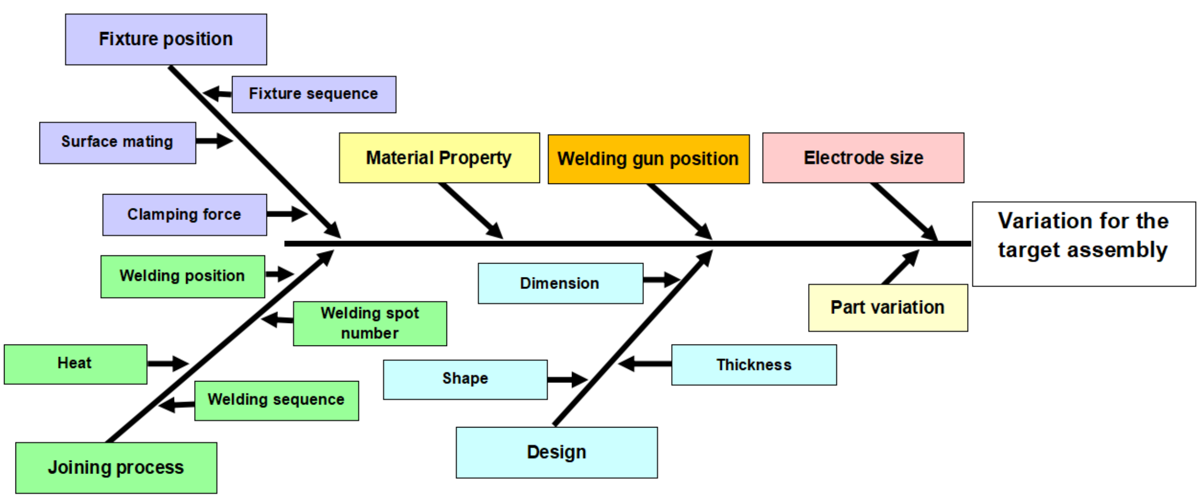


Figure 8: Different parameters of the assembly variation from interviews

Apart from the parameters that were found in the interview, the team also discussed the following potential parameters that could affect the final assembly.

- Part variation: As stated in the interview by the engineer, the part variation could be one source for making some geometric problems. Each part has somehow variation obtained from their corresponding production process. There are different reasons for making a part variation, such as production temperature, residual stress, machine problem.

- Welding time: The heat generated by the electrical resistance, the welding time that the current is applied. The energy applied in the interface of sheet metals depends on the amount of welding time since welding time has a positive correlation with the applied energy for the assembly.

- Electrode pressure: A corresponding pressure for the electrodes is applied in the welding process since the amount of pressure could affect the resistance between the sheet metals and the electrodes, the pressure would also affect the generated heat and geometric variation.

3. ***Do you have any ideas or suggestions for improving the geometric problem?***

The answers to this question are very different, they are classified into five different types.

- Simulation: As discussed in the first general question, the potential parameters should be simulated in relevant software, the most influential parameters should be included and analyzed in the simulation, such as welding spot number and sequence, heat, parts variation, etc. The purpose of this kind of simulation is to find the effect of different parameters, after the simulation the next step is to find a method to reduce the effect of the parameters.

- Design: One engineer mentioned that the design could influence the final deflection. For example, the variation result from a better design could be different. The design shape and dimension could be improved for the assembly, such as thickness, length, etc.

- Material: Some engineers explained the material of the parts could be changed, since better material which has less deformation from heat and less strain from the stamping process.

- Other possible joining processes: 4 out of 8 interviewed engineers mentioned it might be possible to try other joining processes for some assembly parts. For example, laser welding or glue process could be good choices since they have less heat generated and more accuracy, however, it should be investigated more for other processes because the glue could be easily deformed when the assembly is heated. One important point from engineers is that some 'compensation' change could be made from the stamping process if there are reliable variation would happen from the simulation and real part.

- Welding robot: One engineer mentioned that it is very hard to synchronize the welding gun with the deflected part. The reason is after a different welding process, some parts of the assembly will have some variation from the welding. It is hard for a welding gun to match the welding position from the original coordinate with the coordinate of a deflected part. One possible solution could be synchronizing the robot programming with the coordinate from the deflected part.

The previous experts' improvement suggestions are illustrated in Figure 9 below:

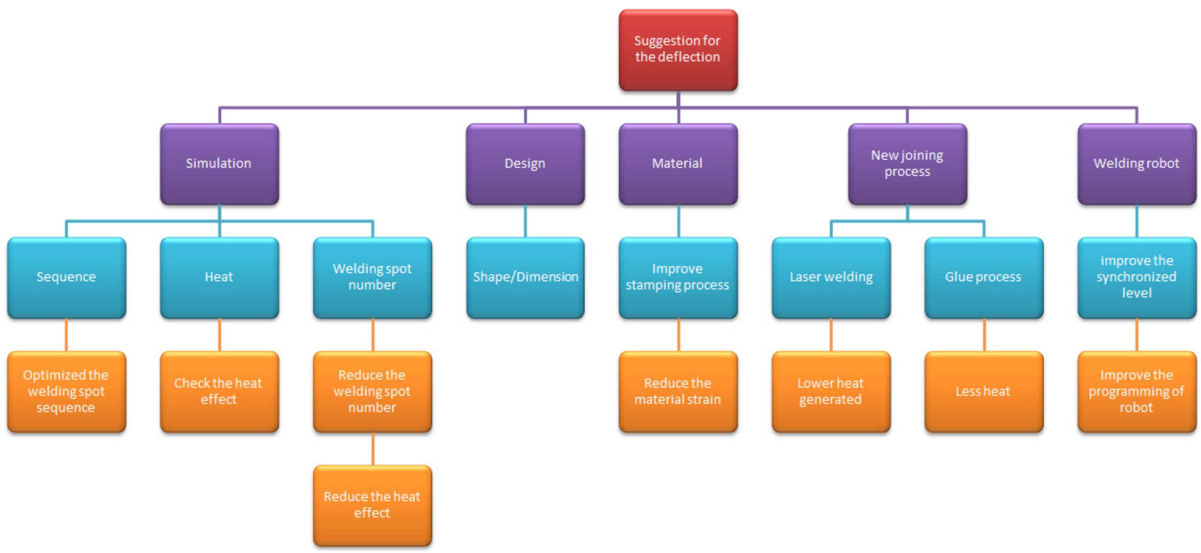


Figure 9: Suggestion for the deflection

II. Specific questions for the target assembly case

To get more understanding about the geometrical problems of the reference assembly, presented in section 2.4.2. general questions about the expert's ideas were asked. The problem is the geometry deformation of the assembly presents as bending in the middle area of the assembly, see Figure 3.c. Prior to this study, several efforts and experiments have been performed to identify the source of this issue. Physical experiments have been performed with different conditions. Mainly by changing the exerted head parameter, cooling time and preheating.

Some specific questions are proposed in Table 1 to the participants according to their corresponding working area. The purpose of asking the specific questions is to get more detailed information from their specific perspective about the geometrical problem. Part of the specific questions are shown in the following table, some statements from the engineers are cited and some statements are taken away due to the confidential concern, then the statements are transferred into reflection. The content of the interview could be checked in Appendix A.

Specific questions	**Statement of interviewees**	**Reflection of Statement**
How does the welding group work with geometrical problems?	*'Different experiments depend on experience.'*	The experiment should be made from both scientific simulation and practical experience.
What is the geometric result after the cooling experiment?	*'The test of increasing the cooling time for each spot was about 30 minutes, but the geometric issue occurs in the same value.'*	It means the 'cooling time' parameter has not a big influence on the deformation and it is not practical in the real production context due to the cycle time.
Do all the shapes have a geometrical problem?	*'We have a flat floor and it still has a deflection.'*	It means the deflection could happen in different parts regardless of the shape.
If preheat the part, will this decrease the heat influence?	*'Maybe, but it might make the part harder. Besides the difficulties of process implementation'*	It might need to be investigated in a material science context but not a geometry assurance context.
Did the welding team check, in which assembly stage the bending happened?	*'It might happen in the last station, where the re-spots of the beam. The most important factor is spot welds.'*	The number of welding spots could affect the final deformation. The more welding spots the assembly has, the more heat will be generated.

Table 1: A part of interpreting of interviewees' statement

4.2 Survey results & analysis

The survey consists of two parts, the first one is the general survey, which was made for finding the participants' opinions about the given welding cases. The second survey is the floor assembly study, which shows the details of the assembly welding part. The reason to make two surveys is that the potential solution for selecting the location, number and sequence of welding spot really depends on the specific issues. Therefore, the first general survey could get a universality about the spot-welding process and the second survey could get a particularity for the target assembly part. Totally 19 engineers participated in the survey, the details of the general survey could be checked in Appendix B.

4.2.1 The general survey

The first survey was used to get how the welding experts and relevant engineers think about the geo-spot selection, how many they would choose for some general shapes and products, why the previous geo-spots were selected. To do so, some open questions are used in the survey to provide freedom for people to add. This research tool was chosen because of the specific subject. Another reason is that engineers could be easily reached in this way due to time and geographical limits.

The survey is created by using Google Sheet due to the simple layout and function. The questions included are created with a careful discussion within the team and the supervisor to get the intended information. The number of questions in the survey is limited and needs around 15 to 20 minutes to finish since their available working time was considered before making the survey. It includes three sample cases and each case presented as a typical example, the first case is a one Flat-hat shaped plate, the second case is two L shaped plates and the third case is two sheets with curved flanges, they are presented in the following Figure 10.

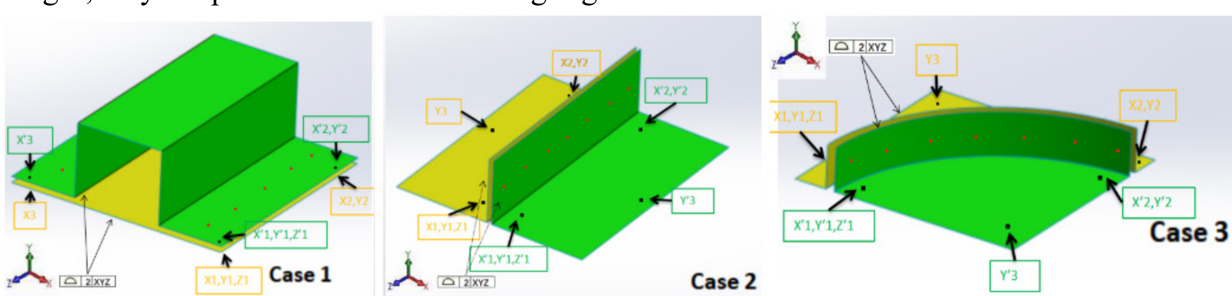


Figure 10: The three sample cases in the general survey

4.2.2 Analysis for the general survey

As shown in Figure 11, around 90% of the participants are either from design or manufacturing sector, around 70% of them have been working for more than 5 or 10 years.

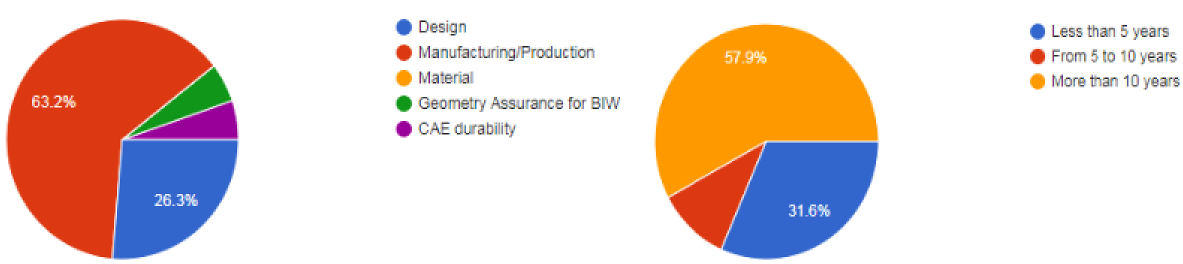


Figure 11: Survey participants information

As for their individual opinion about the general sample cases mentioned in Figure 10, their answers are relatively presented as a normal distribution map, which is concentrated distribution. Shown in Figure 12, for case 1, 13 out of 17 participants chose to set 4 geo-spots. For case 2, 11 out of 17 participants chose to set 2 geo-spots. For case 3, 16 out of 19 participants chose to set 3 geo-spots. The distribution graphs in Figure 12, show the participates have given relatively similar choices.

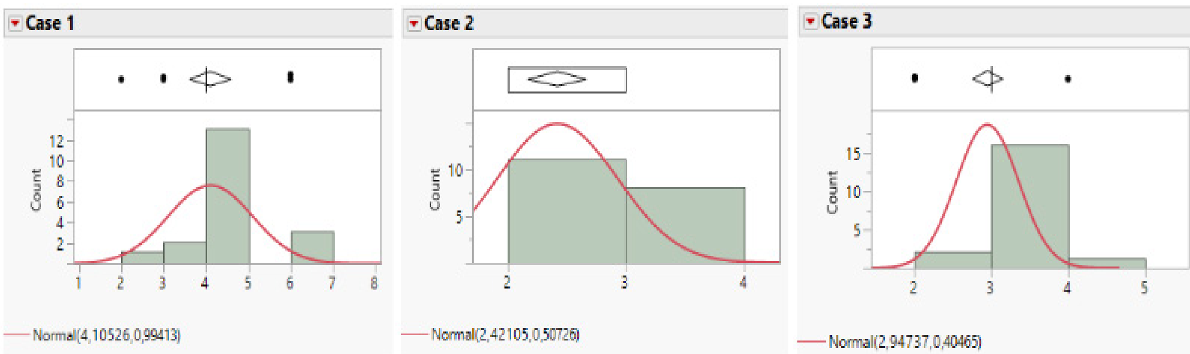


Figure 12: Answer of geo-spot number for sample cases

In order to know their opinions about the parameter importance to select the location and sequence of geo-spot for these general cases, they are asked to rank the potential parameters from less important 1 to very important 5, the average importance was accounted from the sum of importance in the following priority list. The parameters have been:

- Cycle time: considering the cycle time while selecting geo-spots.
- Thickness: considering the sheet metal thicknesses while choosing the geo-spots.
- Distance between the geo-spots: considering the distance that the weld points have with each other. Geo-spots should be spread around the geometry.
- Welding gun program: considering the accessibility of the weld points, and the way the robot path is programed (with regards to the cycle time) to select the geo-spots.
- Fixture: analyzing the fixture and select the weld points accordingly.
- Heat: considering the heat generated during the welding process.
- Geo-spots number: considering the number of geo-spots applied in the assembly parts.
- Geometrical mating: considering how the assembly parts mate with each other before the welding process.

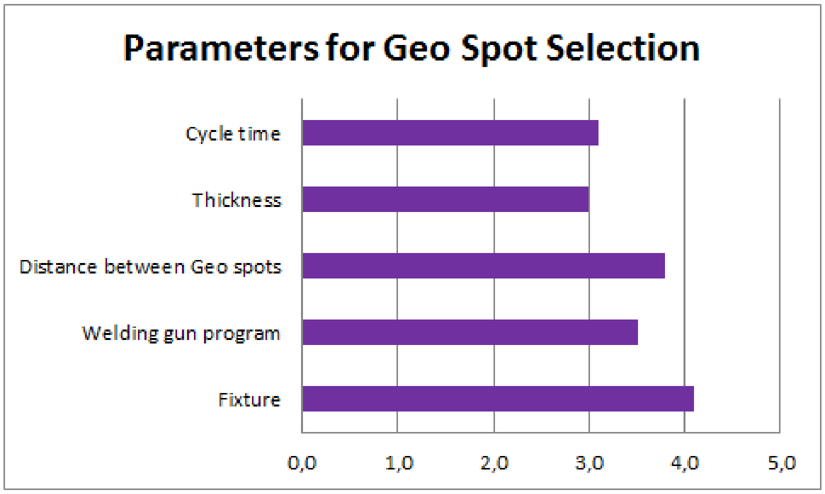


Figure 13: Parameter importance for *Geo-spot*'s location selection

As shown in Figure 13, the parameter Fixture (the fixture that used to fix the assembly parts), Distance between Geo-spots (the distance between two nearby geo-spots) and the Welding gun variation (the accessibility of the weld points, and the way the robot path is programed) are the top three important parameters according to the participants' opinion.

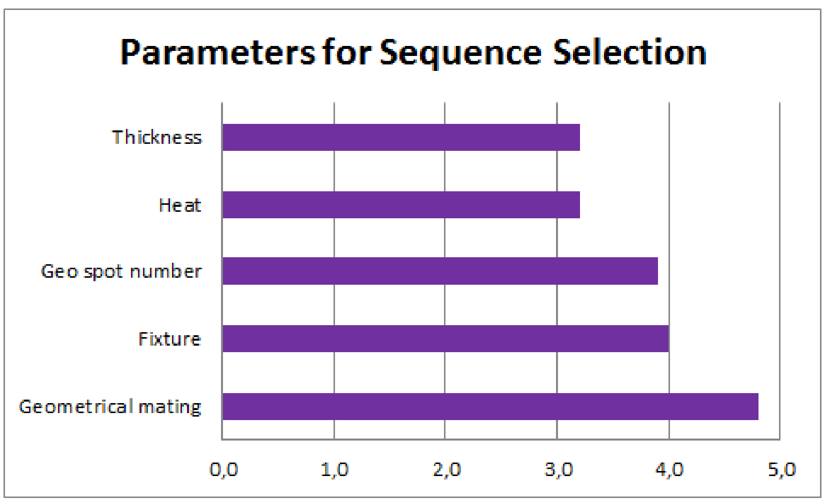


Figure 14: Parameter importance for *Geo-spot*'s sequence selection

For the geo-spot sequence selection in Figure 14, the Geometrical mating (the way how the assembly parts matched with each other), the Fixture (the fixture that used to fix the assembly parts), and the geo-spots number (how many geo-spots applied in the assembly parts) are the top three critical parameters.

4.2.3 The floor assembly study

As mentioned by the engineers in the interview process, the influential parameters depend on the specific context. Therefore, in order to get the specific feedback for the research target, a floor assembly study was sent out to the relevant engineers. 20 answers are collected from the participants. The target part could be checked in the following picture in Figure 15, the whole part is not allowed to show due to the confidential issue of the company.

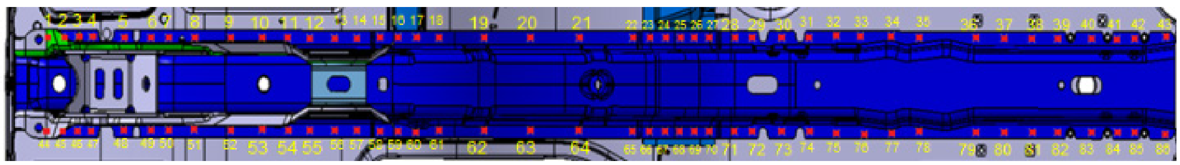


Figure 15: The picture of the target part

4.2.4 Analysis for the floor assembly study

There are four questions in the floor assembly study, which asked about the location, number, and sequence of geo-spots, what is the potential reason behind a geometrical deformation. The details of the floor assembly study could be checked in Figure 3 and Figure 15.

In the beginning, they were asked to give their opinion about the current welding sequence, which shows in the following Figure 16 that more than 50% of the participants are either not sure or disagree with the current welding sequence. For those who choose 'yes', the reason behind it is either from intuition or experience, none is made by investigating by the CAE software. Thus, a more scientific method is in need.

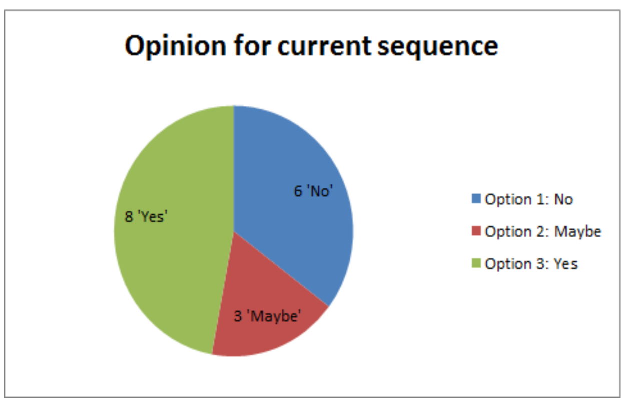


Figure 16: Pie chart for the current sequence

The first question was to ask setting the number of geo-spots, there are 4 options for them. As shown in the following Figure 17, 53% of the participants choose to set 10 to 15 geo-spots for the target assembly.

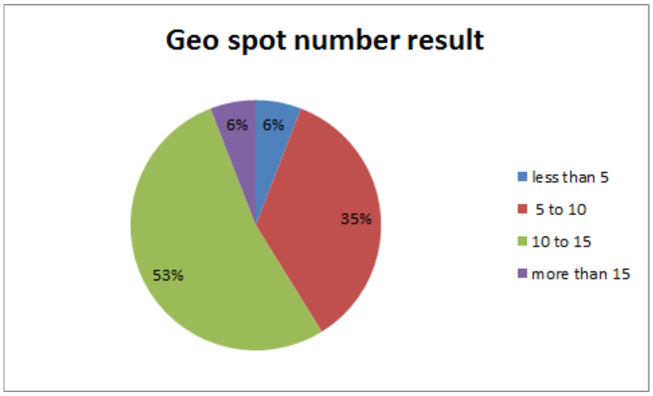


Figure 17: Pie chart for the *Geo-spot* number selection

The second question was to ask the specific reasons for setting the geo-spot number. After sorting all the collected answers, there are mainly three reasons for making the selection. The first reason, which 10 out of 17 participants gave a similar reason, is to fix the parts and secure they are one the correct position. The second reason, which 4 out of 17 participants gave a similar reason, is to distribute the geo-spots on the continuous segments. For instance, one participant suggested- 'divide the assembly into 3 parts, each part set around 4 geo-spots'. The third reason is about the cycle time on the production line, in which 3 out of 17 participants gave similar answers. All the 3 participants think the cycle time should not be too long in the production line, which could lead to a faster spot-welding process with fewer obstacles.

First reason: 10 similar answers	**Second reason: 4 similar answers**	**Third reason: 3 similar answers**
Fix the part and prevent twisting	*Not get a too long distance for geo spots*	*Cycle time*
Set key points with the profile	*Since it is a long part I would put 6 welds*	*Keep cycle time not too long*
Keep a balance with geospot number	*the width of the blue part has to be locked*	*Load distribution between robots*
Secure beam and plate before lift up	*Divide to 3 part, each part 4 geo spots*	
Keep initial geometry and fix the part		
Fix the assembly		
Fix the position for the geometry		
Connect it to surface with shape		
Geometry of the part		
To assure good fit prior re-spot		

Table 2: The inductive analysis of the collected answers

The third question was to ask the participants to set the geo-spot location for the specific assembly. There is a total of 86 possible spots that can be chosen, according to the geo-spot number they had chosen in the first question, they could pick the specific location of the geo-spot. After collecting all the answers, there was a need to analyze the options they had chosen and pick the suitable geo-spot sequences for running the simulation.

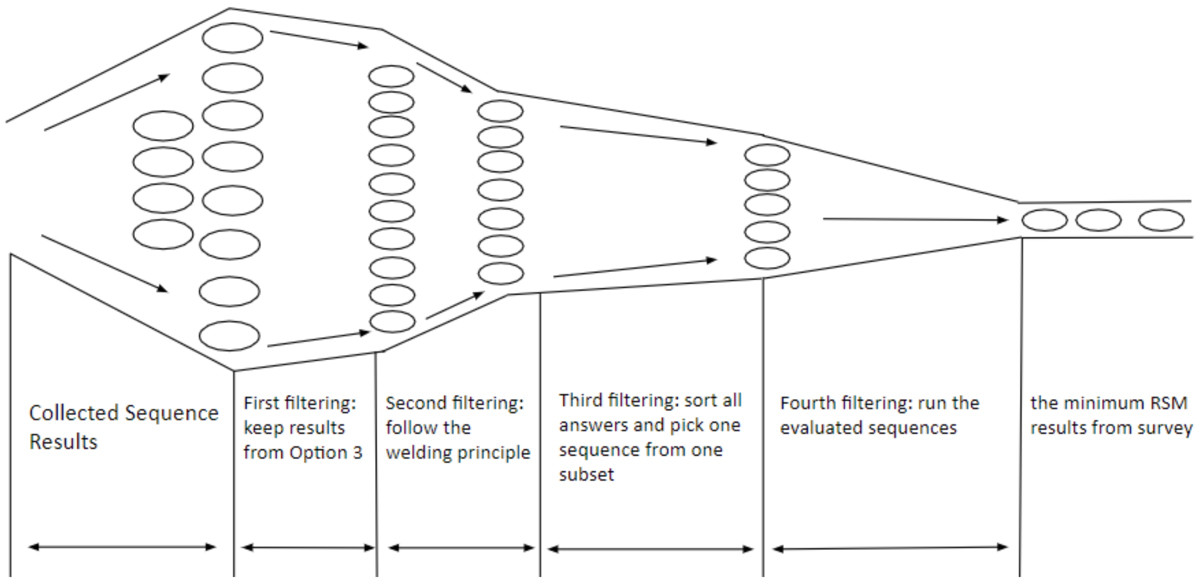


Figure 18: The filtering tunnel for the collected survey answers

There are mainly 4 steps to filter the collected results, which is explained in Figure 18 as following steps:

The following options in the floor assembly survey are considered for filtering:
Option1: Setting less than 5 geo-spots for the target assembly
Option 2: Setting from 5 to 10 geo-spots for the target assembly
Option 3: Setting from 10 to 15 geo-spots for the target assembly
Option 4: Setting more than 15 geo-spots for the target assembly

Step 1: Keep the result from option 3 (setting the geo-spots number from 10 to 15), since more than half of the participants chose it as shown in Figure 16 and some different sequence experiments with option 2 already done at the company before.

Step 2: Exclude the sequence results that are out of the basic welding principle. The basic welding principle applied in this case is mentioned by Liu and Hu- 'to weld from weak to strong'[28]. The way to find the 'weak' part was inspired by the special case of Figure 8 (a) in [5]: since the welding points from the 'weak' area could close the biggest gap and prevent potential distortion of the assembly. It was assumed the 'weak' area in the floor assembly located in the middle area of the welding path. However, just in case it was not the right area, the welding sequences from the side area were also kept. Therefore, some sequence results were excluded.

Step 3: Sort the different sequences from option 3, classify the similar welding sequence into one subset, for example, one subset could be welding from middle to sides, another subset could be from sides to the middle, etc. After the classification step, one welding sequence was chosen from each subset with the help of experienced welding engineers, therefore, 5 sequences are picked from 5 subsets.

Step 4: Run the evaluated sequences, 5 simulations are executed by RD&T to get the RMS results and compare them.

The fourth question was to ask the participants to give the possible deflection parameters for the target assembly part. As presented in the following Figure 19, Welding spot number, Geo-spot sequence and Heat are the top three important parameters. In order to check the specific effect of the important parameters, some feasible parameters are chosen in a Design of experiments simulation in Chapter 5.

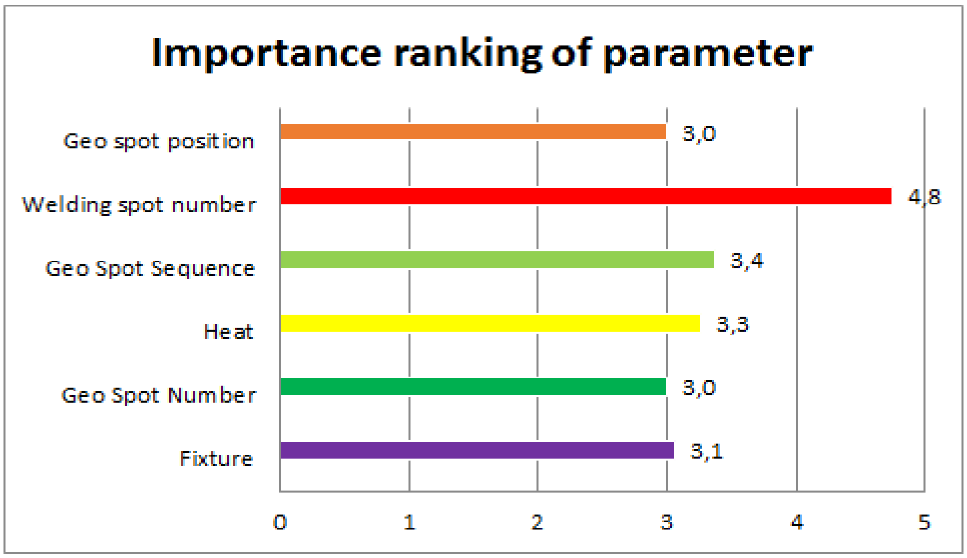


Figure 19: The importance ranking of the floor assembly study

4.3 Simulation results of the survey

After the filtering step, in order to check the geometric results of different welding sequences, the five different sequences are implemented in RD&T software. As shown in the following Table 3, there are 3 improved results from participants, the best result is from Engineer 3 with 67.5% improvement when compared with the current sequence result. The best result will be compared and discussed with other simulation results in Chapter 7.

Participant	Welding Sequence	RMS MM	Improvement (%)
Engineer 1	23, 60, 9, 46, 3, 52, 16, 70, 36, 85, 42, 79	1.06	33.75
Engineer 2	21,64, 18, 61, 5, 44, 12, 52, 28, 71, 35, 80, 41, 86	1.94	-21.25
Engineer 3	20, 63, 25, 68, 38, 81, 16, 60, 6, 50	0.52	67.50
Engineer 4	19, 62, 5, 48, 12, 54, 40, 83, 28, 72	1.95	-21.88
Engineer 5	3, 46, 12, 55, 42, 85, 30, 73, 23, 66, 16, 59	1.02	36.25

Table 3: The simulation results of the floor assembly study

5 DoE simulation

As explained in Chapter 4, during the interview and survey process, there are some critical parameters for setting the geo-spots sequence and location that introduced by the participants. Therefore, a DoE was implemented in the project to find the individual and interaction effect of the selected parameters for the target floor assembly. An experimental plan was made, and the respective simulation was done, the results from the effect are plotted in the normal probability paper to show the active factors.

5.1 The experimental plan

After analyzing the results from the survey, a few important parameters were proposed by the participants, however, due to the limitation of the project, there are a few possible parameters that could be investigated by using RD&T software. After discussing with the key stakeholders in the project, 3 important parameters were chosen in the DoE simulation which is explained in the following section.

Factor A, which is the distance between two nearby geo-spots, the location of the two nearby geo-spots will be changed according to their corresponding distance to the middle point of the beam. An example of Figure 20, factor A is the distance between point A and point B.
Factor B, which is the number of geo-spots. For example, factor B is the three geo-spots (point A, point B, and point C) in Figure 20.
Factor C, which is the welding sequence based on the distance from the geo-spot to the nearest locator. For example, the welding sequence in Figure 20 is B-A-C.

Process parameters	**Label**	**Low level**	**High level**
Distance between two nearby geo-spots	A	-1	+1
Number of geo-spots	B	-1	+1
Welding sequence based on the distance from the geo-spots to the nearest locator	C	-1	+1

Table 4: List of chosen parameters for the experiment

Take the Case 1 model in Chapter 4.2.1 as an example, assume there are 3 geo-spots (spot A, B, and C) and 4 fixtures (fixture 1, 2, 3, 4) in the welding case. The factor A, in this case, are the distance between A and B, B and C, A and C. Factor B is three geo-spots in this case. Factor C is the welding sequence according to the distance to the nearest locator, which is B-A-C in this case, Figure 20 illustrates the three different factors in Case 1.

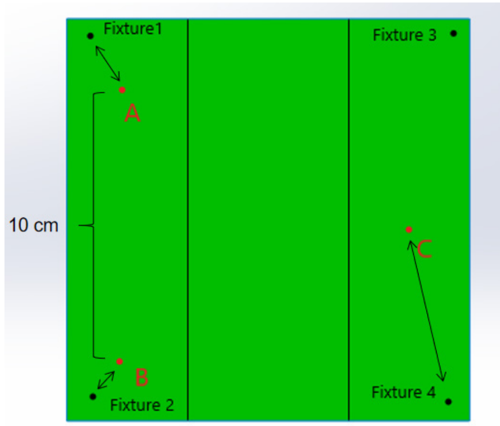


Figure 20: The illustration of Case 1 for the three different factors in DoE

The outcome is RMS of geometrical variation, which shows the deviation level of the assembly.

Experiment order	**Standard order**	A	B	C	AB	AC	BC	ABC	RMS MM
(7)	1	-	-	-	+	+	+	-	1.48
(6)	2	+	-	-	-	-	+	+	1.98
(4)	3	-	+	-	-	+	-	+	1.62
(3)	4	+	+	-	+	-	-	-	1.89
(8)	5	-	-	+	+	-	-	+	1.48
(1)	6	+	-	+	-	+	-	-	1.45
(6)	7	-	+	+	-	-	+	-	1.59
(5)	8	+	+	+	+	+	+	+	1.46
	Effect:	0.153	0.043	-0.248	-0.083	-0.233	4.900	0.033	1.619

Table 5: Result of the experiment

5.2 DoE Result Visualization

After performing the scheduled experiments, the results of effects from individual parameter shows that the factor C, factor AC, and factor BC have relatively more significant effects than the rest, which could also be checked in the following Table 6. One comment needs to be pointed out is that the DoE results mainly depend on the geometrical deviation of part level, some different DoE results could be also generated in other contexts.

Effect of different factors	Significance effect result
Factor C	-0.2475
Factor AC	-0.2325
Factor AB	-0.0825
Factor ABC	0.0325
Factor B	0.0425
Factor A	0.1525
Factor BC	4.9000

Table 6: The effect results of DoE

Moreover, the results of individual effect are visualized in Figure 21, according to the value of parameters' slope, the factor BC (number of geo-spot interacted with welding sequence of the nearest locator) has the biggest effect for the RMS results compared with the rest 6 factors, which visualized the effect results of factor A, factor BC, factor C and factor AC in Table 6.

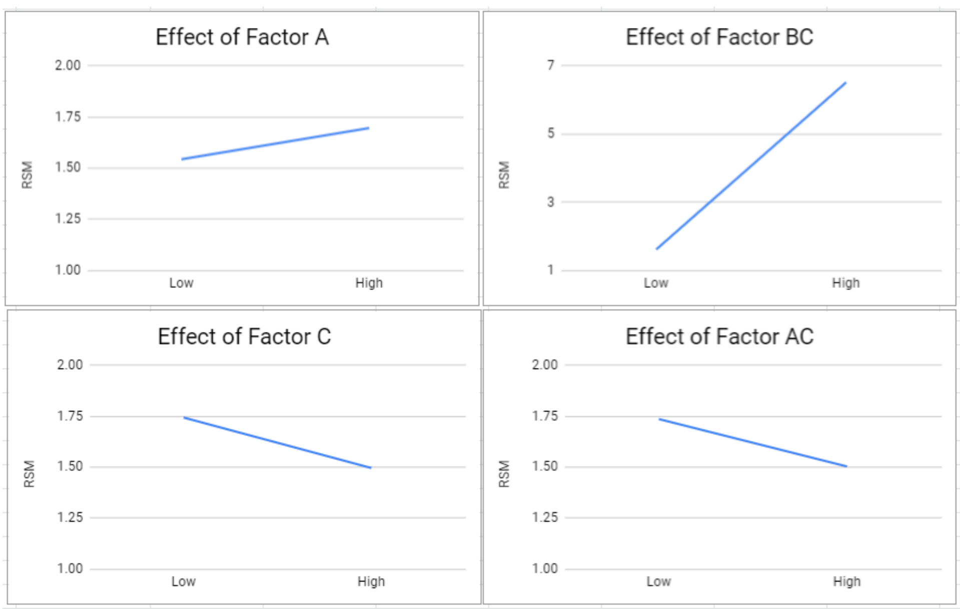


Figure 21: the visualization results of individual effects

The results of the interaction effect are presented below, which clearly shows the interaction effect between every two factors. As shown in Figure 22, the interaction between Factor A and Factor C and the interaction between Factor B and Factor C are concurrent. It means they have a substantial effect, However, the interaction effect between Factor A and Factor B is almost parallel, it means they have a low interaction effect between each other.

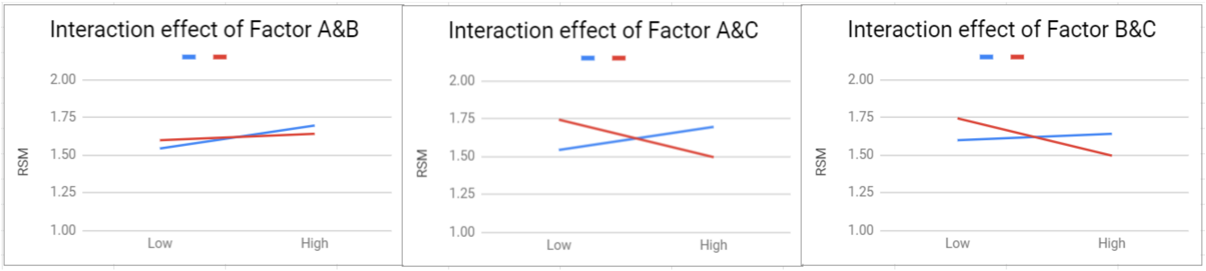


Figure 22: The interaction effects

The analyzed results from the DoE are dependent on the geometrical deviation of the individual parts. In case of changes in the part deviation, the interaction between the parameters will get influenced. Therefore, this analysis is solely dependent on the analysis of the presented floor assembly with a specific part deviation.

5.3 Normal Probability Paper Plot

In order to check the active factor and inactive factor in the experiment, a normal probability paper plot was done. By plotting the results of the experiment, a normal probability graph was made. As presented in Figure 23, it shows that the Factor BC and Factor C are far away from the orange line, which means these two parameters are active and have a higher effect on the results RMS of geometrical variation if compared with the rest parameters. On the other hand, it means the factors on the red line are inactive, which means they have relatively less effect for RMS.

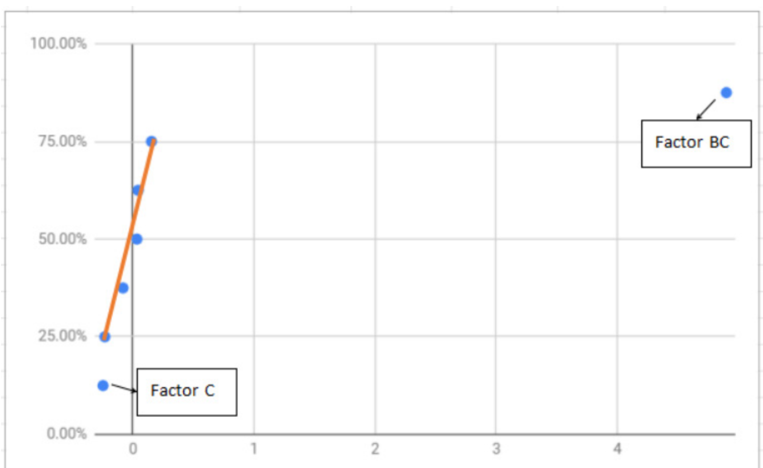


Figure 23: Normal Probability Plot

By checking the result of Figure 23, it is understood that the welding sequence based on the distance from the geo-spot to the nearest locator (factor C) and the number of geo-spot interacted with welding sequence of the nearest locator (factor BC) is important when deciding the location of the geo-spots.

6 Simulation-Based Optimization

Since the change of the welding sequence has a big influence on the geometry variation assembly, there is a need to find the optimal sequence for minimizing the sequence effect. Therefore, the sensitivity-based algorithm introduced in Chapter 2.3 was implemented to propose the optimal welding sequence [7]. The followed algorithm structure can be illustrated as below:

1. Simulate the variation/deviation for all individual spots weld. For example, an assembly with five welding spots, one deviation simulation of each spot: 1, 2, 3, 4, 5 is executed to check the impact of each welding spot on the geometry outcome, how sensitive the geometrical variation of the assembly is for each spot alone.

2. Choose the spot with the lowest variation influence and set it as the first spot in the sequence. For example, spot 3.

3. Simulate the variation\deviation of the individual remaining spots with considering the chosen spot in the simulation. For example: 31, 32, 34, 35.

4. Repeat steps 2 and 3 until all the spots are set.

For executing the optimization method for $(\boldsymbol{n})$ welding spots, $\frac{\boldsymbol{n}*(\boldsymbol{n}+\mathbf{1})}{\mathbf{2}} - \mathbf{1}$ simulation runs are executed which in turn are divided into n iterations; therefore, for each iteration, one spot gets its order in the welding sequence.

In the floor assembly, a sensitivity-based algorithm was applied to propose the optimal sequence of the nine geometry spots. The number and position of the Geo-spots that were user-predefined in the assembly process are fixed. The deviation simulation result of the current spot-welding sequence followed in the assembly process, that was set by experience, was used as a reference for evaluation and comparison. 44 runs for the simulation are needed to define the welding sequence for nine geo-spots. The detailed results of the sensitivity simulation could be found in Appendix C. The results are shown in the below table:

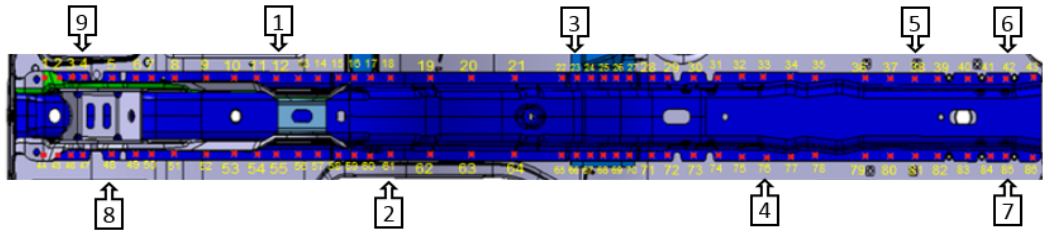
Sequence	**WP 1**	**WP 2**	**WP 3**	**WP 4**	**WP 5**	**WP 6**	**WP 7**	**WP 8**	**WP 9**	**RMS mm**	**Improvement**
Current Seq	1	2	3	4	5	6	7	8	9	1.60	(Reference)
Optimal Seq	6	3	4	8	2	5	7	1	9	1.39	13.12 %
Random Seq	9	2	4	6	1	7	8	5	3	1.50	6.25 %

Table 7: The different RMS resulted in mm and the improvement obtained for different geo-spots sequences

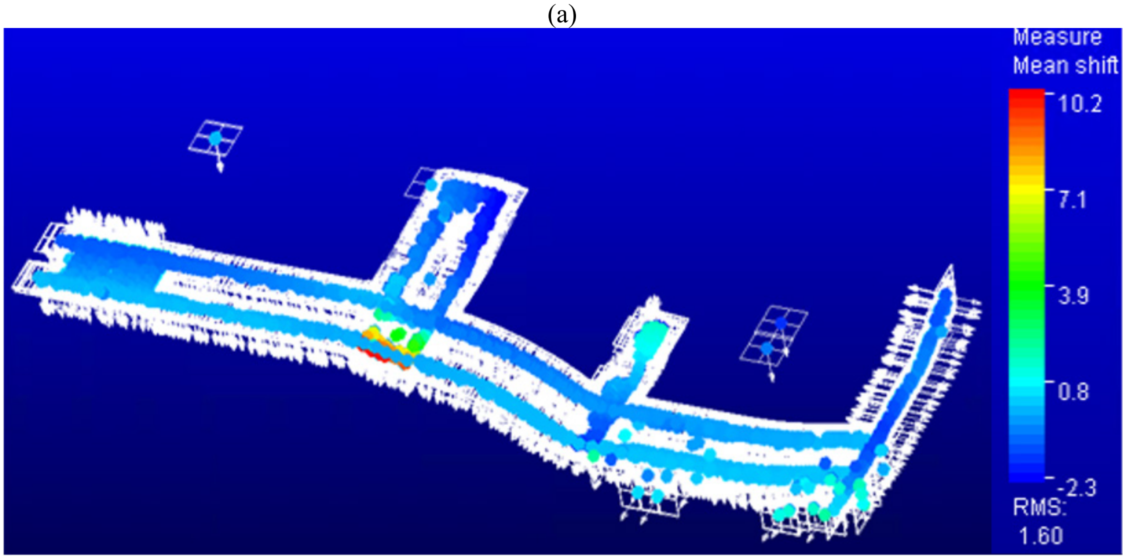
Table 7 shows that following the optimal sequence obtained from the sensitivity-based algorithm gives lower deviation, lower RMS value 1.39 mm compared to 1.6 mm and 1.5 mm that was given by the current sequence and random sequence respectively. 13.12 % of the improvement was achieved after rearranging the order of setting the same geo-spots used in the current assembly sequence.

In Figure 24, the geo-spots sequences and deviation simulation results for current and optimized sequences are illustrated, where (a) and (c) the current and optimized sequences, (b) and (d) the deviation simulation results for the current and optimized sequences are shown using RD&T software.

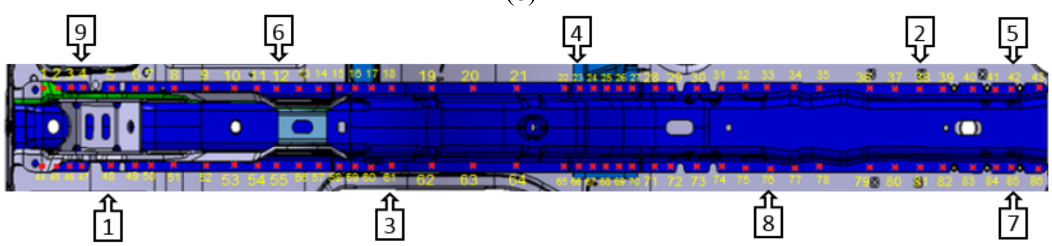
The further calculation was done for more verification of the optimized sequence obtained. The influence of setting the re-spots on the final deviation for both current and optimized sequences was investigated, through executing the geo-spots and re-spots deviation simulation for both sequences. The change of the deviation after the re-spots welding step was observed. The deviation of the welded assembly that followed current sequence geo-spot was decreased by 48.75 %, whereas the one that followed the optimized sequence was decreased by 41.72 %, which is not as much as the current one, that makes following the optimized geo-spots sequence partly fulfills the third criterion of geo-spots more than the current one.



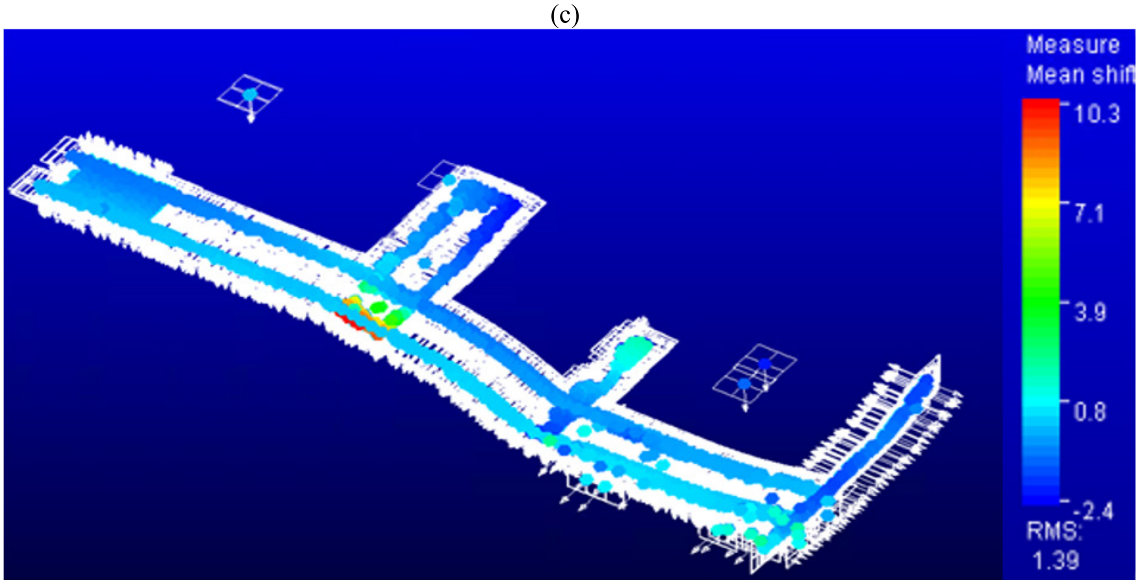
(a)



(b)



(c)



(d)

Figure 24: Current and optimized simulation result.

7. Analysis and comparison of the simulation results

This chapter presents the analysis and comparison of the simulation results of the survey and optimization outputs. It provides an explanation of the results and the reason for the corresponding improvement.

7.1 Simple cases analysis and comparison

Two of the general cases presented in the survey were randomly chosen and simulated using RD&T software Figure 25. The purpose of the simulation was to demonstrate the results of the variety of geo-spots selection and sequence proposed by the experts.

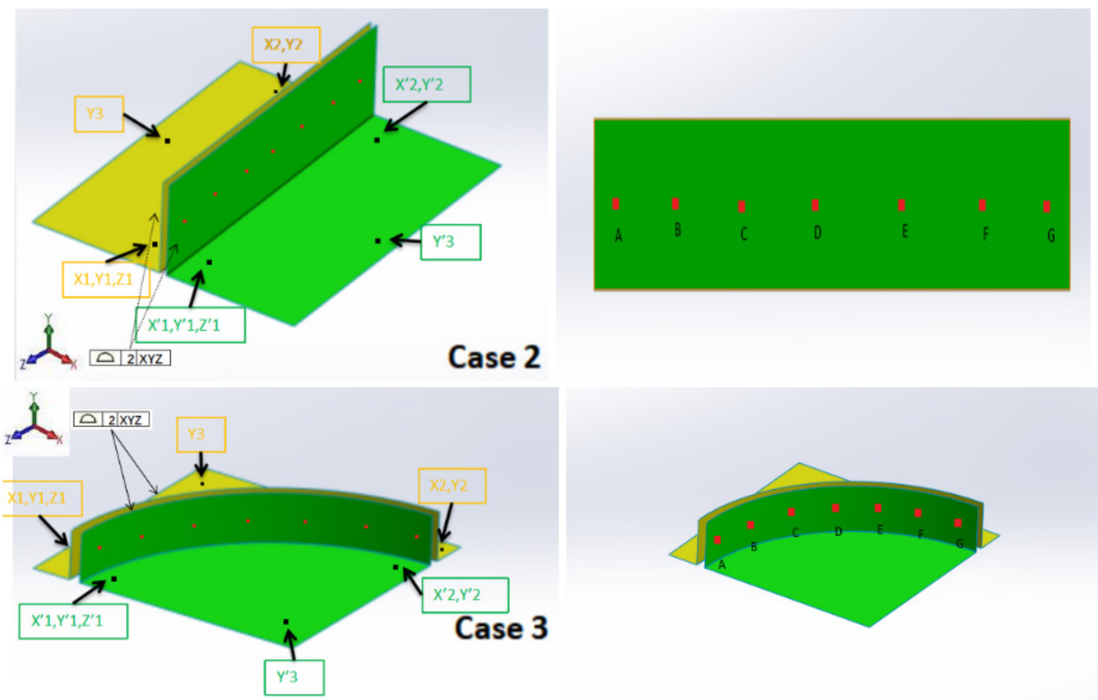


Figure 25: Two simple cases simulation in the survey

Case 2		Case 3	
Number, Position, Sequence and Repetition	**RMS mm**	**Number, Position, Sequence and Repetition**	**RMS mm**
B, F (5)	1.06	A, D, G (5)	0.24
C, E (1)	0.67	**D, A, G (5)**	**0.13**
A, D, G (3)	0.43	A, G, D (1)	0.27
A, G, D (1)	0.44	D, F, B (1)	0.18
D, A, G (2)	0.45	D, B, F (1)	0.15
A, G (4)	0.51	A, G (2)	0.44
D, B, F (1)	**0.34**		

Table 8: Simulation results of the two simple cases

Table 8 shows the variation represented as RMS for each geo-spot set (number, position, and sequence). For each simple case, different repeated choices based on the experience were presented, most of the selections have relatively close RMS, but the relative difference between the highest and lowest obtained RMS is considered high.

The diversity of the experts' choices and its consequence variations shows the difficulties that the experts face when estimating the influential factors during the geo-spots' selection, especially for the multi-dimensional data. The use of CAT simulation tools is essential for this purpose. The geo-spots parameters investigation should be performed initially to evaluate the response of the assembly to different parameters. Thus, more appropriate geo-spots parameters can be selected for further optimization and improvement.

7.2 Floor Assembly Case Analysis and Comparison

Analysis and comparison of the results of the five suggestions selected from the survey were illustrated below:

Suggestion 1: The geo-spots parameters are illustrated in Figure 26 below:

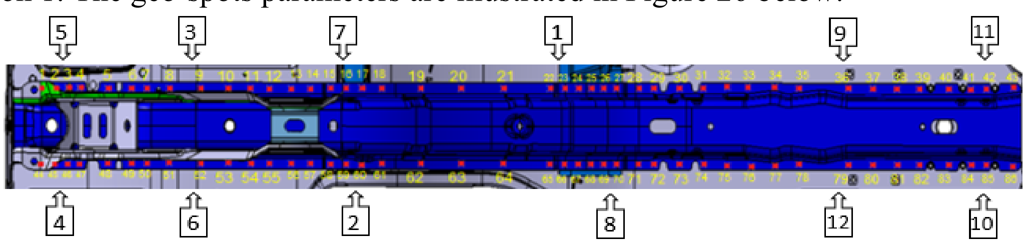


Figure 26: Geo-spots number, position, and sequence of suggestion 1

Suggestion 2: The geo-spots parameters are illustrated in Figure 27 below:

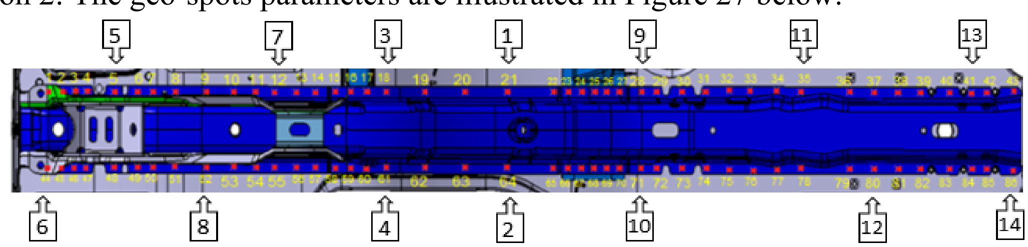


Figure 27: Geo-spots number, position, and sequence of suggestion 2

Suggestion 3: The geo-spots parameters are illustrated in Figure 28 below:

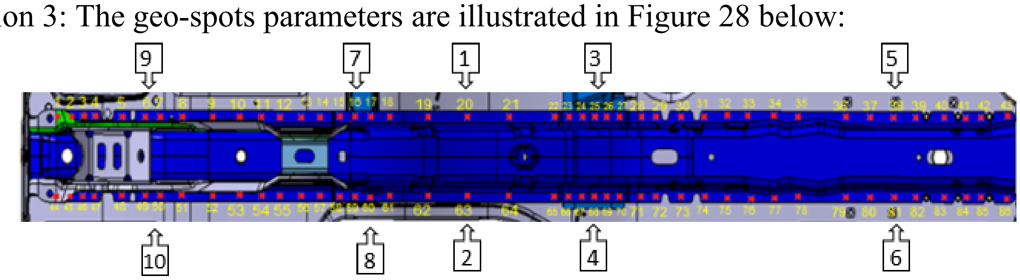


Figure 28: Geo-spots number, position, and sequence of suggestion 3

Suggestion 4: The geo-spots parameters are illustrated in Figure 29 below:

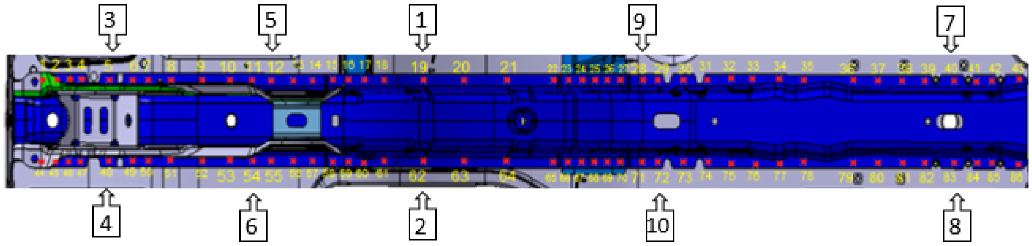


Figure 29: Geo-spots number, position, and sequence of suggestion 4

Suggestion 5: The geo-spots parameters are illustrated in Figure 30 below:

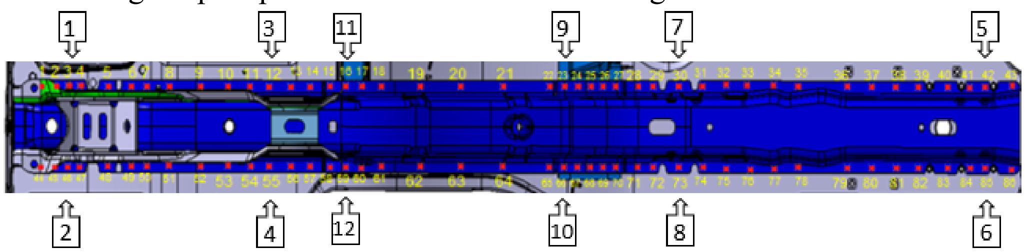


Figure 30: Geo-spots number, position, and sequence of suggestion 5

Suggestion Number	Welding Sequence	RMS mm	Improvement (%)
Suggestion 1	23, 60, 9, 46, 3, 52, 16, 70, 36, 85, 42, 79	1.06	33.75
Suggestion 2	21, 64, 18, 61, 5, 44, 12, 52, 28,71, 35, 80, 41, 86	1.94	-21.25
Suggestion 3	20, 63, 25, 68, 38, 81, 16, 60, 6, 50	0.52	67.5
Suggestion 4	19, 62, 5, 48, 12, 54, 40, 83, 28, 72	1.95	-21.875
Suggestion 5	3,46,12, 55, 42, 85, 30, 73, 23, 66, 16, 59	1.02	36.25

Table 9: The deviation results and the improvement compared to the current welding set

The simulation comparison for the experience-depended choices of the geo-spots number, position and sequence showed a wide variety of the result Table 9, since a small change in the geo-spots parameters might cause a significant change in the outcome which is difficult to be predicted.

It can be noticed that:

1. Suggestions 1&5: both suggestions have the same geo-spots numbers (12 spots) but different spots location and different sequences. Same RMS values were resulted (1.06 & 1.02).

2. Suggestions 2&3: suggestion 2 has 4 more geo-spots (14 spots) than Suggestion 3 (10 spots), different location and sequence, but different RMS results where suggestion 2 has RMS value almost 4 times the suggestion 3 RMS value (1.94) compared to (0.52).

3. Suggestions 2&4: Suggestion 2 has 4 more geo-spots (14 spots) than suggestion 4 (10 spots). Different location and sequence, Same RMS values were resulted (1.94 & 1.95)

4. Suggestions 3&4: Both suggestions have the same geo-spots number (10), very similar spots positions but different RMS results, where suggestion 4 has RMS value almost 4 times the suggestion 3 RMS value (1.95) compared to (0.52).

After analyzing the previous notes, some conclusions are mentioned as below:

1. Setting more geo-spots doesn't ensure obtaining higher geometrical robustness (low RMS Value), as shown in suggestions 2&3.

2. The same RMS value might be obtained for different geo-spots parameters (number, position, sequence), as shown in suggestions 1&5 and 2&4.

3. Changing the geo-spots welding sequence for the same spots number and similar location might have a significant influence on the resulted assembly deviation, as shown in suggestion 3&4.

4. Following specific sequence direction for specific assembly cases can make a significant improvement. As shown in suggestion 3&4, even the first welding spots were set in the middle of both the assemblies, but in the best suggestion 3 the welding direction started from the middle to the very ends. In contrast, suggestion 4 that showed more deviation, the welding direction started from the ends to the middle.
   Figure 31 shows the difference in the welding direction for suggestions 3&4.

Figure 31: The difference in the welding direction for suggestion 3&4

The simulation results for geo-spots parameters proposed in suggestion 3 showed the lowest assembly deviation compared to other suggestions, even lower than the deviation obtained after applying the sequence optimization for the current geo-spots. That because suggestion 3 has different geo-spots position and number than the current geo-spots set. As the simulation shows in Table 9 the achieved improvement of following the suggestion 3 set is 67.5% compared to the current geo-spots sequence.

Geometry deviation simulation including the geo-spot and re-spot weld spots was executed for more investigation regarding suggestion 3. The result after conducting the re-spots simulation stage showed the total deviation was increased by 28.8%. It could be interpreted that the majority of the deviation occurred in the geo-spots stage. Assuming that those geo-spots number and positions ensure the rigidity of the welding parts during the assembly process, all the above make the suggestion 3 the most appropriate choice that fulfills all the three geo-spots criteria mentioned in Section 3.3.3.1. More improvement can be achieved by applying the same optimization method that was shown in Chapter 6.

Four simulations	Improvement (%)
Survey Result	67.5
Optimized Result	13.1
Random Result	6.3
Current Result	0

Table 10: The comparisons of 4 simulation results

Table 10 shows four different simulation results, which are the survey sequence simulation, optimized sequence simulation, random sequence simulation, and current sequence simulation respectively. The best result shows there is a possible 67.5% geometrical improvement for the floor assembly. The corresponding reason behind the improvement is because of considering the Geo-spot location to the nearest fixture, which was given by the corresponding participants. Moreover, shown in Figure 23, the result of DoE presents that the Factor C (welding sequence of the nearest locator) and Factor BC (number of geo-spots interacted with the welding sequence of the nearest locator) are active factors and could affect the final assembly result. This result in Figure 23 could once again validate the best results from survey simulations.

8. Conclusion and Recommendation

In common industrial fields and especially in the automotive industry, geometry assurance is a critical aspect in the product development and production phases. During the assembly process, a combination of many assembly factors influences the geometry outcome. Finding and improving the most influential factors is a demand to ensure more geometrical robustness and decrease the resulted variation in the final assembly.

In order to achieve an improvement for the previous aims the work plan was divided into steps:

- Preparing a literature review for giving a holistic view of the assembly process and geometry variation sources.
- Gathering the informative data form industrial experts through direct interviews and a survey.
- Pointing out the most influential factors, after analyzing the data and focusing on one of the important factors was done since the capability and time limits.
- Conducting a DoE study based on deviation simulation to determine the most effective geo-spots parameters and the relationship between the geo-spots parameters that influence the geometry variation most.

- Executing sensitivity-based optimization for the geo-spots sequence of the specific case (floor assembly), in order to propose the ability to achieve more improvement for the sequence predefined by experience.
- Conducting deviation simulations for several cases of the floor assembly that have different geo-spots parameters for analysis and comparison purpose, using RD&T simulation software
- Analyzing the outcomes form the previous steps and draw a conclusion and recommendation.

The survey and interviews figured out that the geo-spots number, position, and sequence besides the heat and surface mating (parts variation) are the most influential factors for the assembly variation in the experience perspective. It also shows that the positioning near the fixture location and enlarging the distance between the geo-spots are highly considered when selecting the geo-spots location. Moreover, the parts' geometrical mating areas and the fixture location are the most important factors that determine a good geo-spots sequence.

The DoE simulation results show the number of geo-spots interacted with the welding sequence of the nearest locator and the welding sequence-based from the geo-spot to the nearest locator needs to be considered when deciding the location of the geo-spots.

The optimization simulation results show that for a specific number and position of the geo-spots, more geometrical robustness can be achieved when applying the right welding sequence. The analysis of the different simulation welding geo-spot parameters shows that there is a high possibility to improve the geometrical quality for an assembly by choosing the right position, number, and sequence of the geo-spots. Although relying on the experience for choosing geo-spots parameters gives satisfying results, using variation simulation software to propose and develop the most promising assembly parameters is recommended to obtain a more robust design.

After the analysis and comparison section, some recommendations are proposed for future work:

1. Using a variation simulation tool is strongly recommended to compare, choose, and improve the assembly parameters, which in turn improve the geometrical quality of the final assembly. Thus, time and cost corresponded to physical experiments can be saved.
2. According to the interview results, there is a need to check the effect of heat and the distortion simulation results. Simulation software that includes heat distortion simulation and variation simulation is recommended to be developed.
3. There is still a need to include more assembly factors and validate the simulation outcomes for improving the simulation capabilities and make it more efficient and trustworthy.
4. Time-efficient optimization algorithms are needed to contribute to improving the assembly parameters. In this work, it has been shown that achieving an improved sequence by using the optimization algorithm, a 13 % improvement can be achieved.

5. In the DoE phase, including more factors, such as ‘heat’, ‘re-spots number’ etc. and conducting more full factorial experimental simulations will make a more precise and accurate effect of parameters.

Research continues in this area, and this includes involving the heat and more other factors in the variation simulation, verification, and validation of the simulation results which could make more investigation in the future.

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Appendices

Appendix A: Interview data collection

With engineer 1:

When fixing the workpieces by fixture does any deflection (sliding) happened?
Nominally no but in reality, it happened in tiny values.

How do you fix workpieces during the welding process?
It is not totally fixed as a rigid body, there are some flexible areas away from the welding location.

Is it possible to weld by two or more welding guns simultaneously?
Yes, it is possible and used by now.

What are the tolerances for the welding positions?
(no idea right now but the active surface of the electrode is 6 MM where the flash zone is 17 mm)

How much heat it can be generated during each spot welded and what is the expected increasing after welding?
(the heat generated does not affect the shape deformation. the welding process time for each spot is about 300 ms, the test of increasing the cooling time for each spot was about 3 seconds but the deformation occurs in the same value.)

Do you think the fixture accuracy affects the final assembly variation?
yes, the fixture could influence the result, but the first try without the fixture.

What you think the most possible factors that affect the final assembly?
In each spot, they crimping the material, because of the temperature

part variation before the welding process
we measure the part before the welding process, part tolerance

Do you have any ideas or suggestions for improving the welding process?
I suggest the first step to include the parameters to make a simulation test and see the effect. The sheet will become U shape after the one line spot welding, talk to Mats Lingren who has done a lot of experiments before.

With engineer 2:
What is the intended outcome for GTT Cab for the project?
We don't know the reason behind it, in the project, why it is happening is an important part. We know the bending could happen in the process, but we want to know how much it will happen.

What is the manufacturing process for the floor beam?
The first process step is to fix the sheet, the second step is to weld the sheet by spot welding.

How you choose geometry points? How to set the welding sequence?
GTO has tried the sequence order test before, ask them about the welding sequence.

What do you think about the project? Do you have any idea about it?
In my opinion, I think the design of the beam could affect the deflection, for example, if you make a better design, such as rib sheet and flat sheet, the result could be different, maybe you could propose a better design and check if it is better.

Which phase do you check the bending result?
The GTO checks the bending result after the whole welding process finished.

What is the joining forces for the floor beam?
You could ask GTO about it, you can also ask what kind of gun, force, sequence, etc.

What methodology did the company follow when did the enhancement tries?
Arbitrary tries depending on experience.

What is your expectation regarding the reason for the issue?
The heat effect and the shape/dimension of the part.

Have you tried the nonrigid study simulation method to play with the welding sequences?
No, GTO tried a lot of experiments before.

How do you decide the number, space, sequence for the spot welding points?
CAE decided that.

In Which stage does the bending occur?
No idea. we just measured after producing

Do all the parts within its allowed tolerances?
Yes, they are.

With engineer 3:
How do you decide the spot welding sequence at GTO?
It is a little bit tricky, it depends on the parts, it is from experience, sometimes it changed.

How do you decide the number and position of the welding point?
Sometimes it just depends on the welding man or robot, it is also from experience.

How you define a master location scheme?
Everything should be nominal in this part, everything is in the right way and no gap between each part.

What you think the most possible factors that affect the final assembly variation?
The heat from the spot welding and the material heated to melt and shrink to smaller, they have tried blow the cold air to the spot welding, but no big difference

Do you have any ideas or suggestions for improving the welding process?
I want to take away the spot welding process because too many welding spots generate a lot of heat, I suggest to put some glue instead of the half welding spot, which decreases the welding spot number.

Does it always have the same amount of deflection or it vary?
Quiet similar deflection results from the experiments data

In which shapes does the deflection appear more?
We have a flat floor and it still has the deflection

With engineer 4:

Have you tried any tests before?

No, it is a combination test before.

Do you think the welding gun, force, sequence affect the welding process?

In my opinion, the production may change the process to another process, we have too much spot weld, because it is very cheap, for example, when we do benchmark at BMW, they use different processes, like laser brazing, etc.

What do you think about the possible factors that affect the final assembly?

When in the stamping process, start from the flat sheet, if you have a high strain inside the material, it is a change. maybe preheat stamping. When you weld, you could change the material, the heat itself will affect it. We have tested the different sequence, they didn't see a big difference.

With engineer 5:

Have you done any experiments before?

I have done the sequence before, try to move around, what to lock, you should understand the main function of the part, BIW part,

What you think the most possible factors that affect the final assembly variation?

The heat, the position has a big effect when doing the spot welding, I think the floor beam part deflection is caused by the temperature problem from the spot welding, the largest variation is the welding gun position, watch the welding gun goes in, in the production line, it is done by automatic weld.

Do you think it is a good idea to keep the body cool for a long time?

We have done the air experiment, but just normal temperature, maybe to use the cooler air to decrease the temperature

What about preheating the part to decrease the heat influence?

Maybe, but it would make the part brutal.

What is your suggestion about the problem?

The first step is to check how the heat influence affects it, the second step is the weld sequence.

Appendix B: Survey question

Master Project: Geo Spots Optimization

Hello everyone!

We are two students from Chalmers University of Technology who are working on the master thesis project - Geo Spots Optimization. We would like to have you and your relevant colleagues' experience and opinions about spot welding for the floor beam assembly in order to improve the robust geometrical quality. We know your time is valuable and we appreciate it, so the questionnaire just need around 20 mins to finish.

If you have any question about the questionnaire or you want to share more about your experience, feel free to contact us:)

Thanks in advance for your time and help!
Abbe&Wei

* Required

A few information about you

1. **Question 1: What is your name:** *

____

2. **Question 2: Which area you are working** *

   Mark only one oval.

   - ⬭ Design
   - ⬭ Manufacturing/Production
   - ⬭ Material
   - ⬭ Other: ___________________________

3. **Question 3: How long you been worked in the area** *

   Mark only one oval.

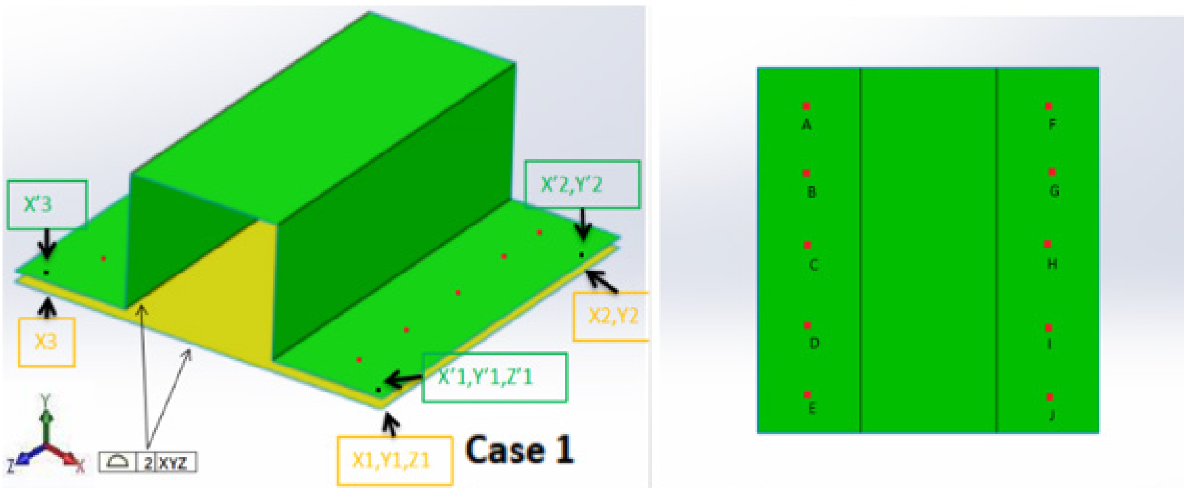
   - ⬭ Less than 5 years
   - ⬭ From 5 to 10 years
   - ⬭ More than 10 years

In the following picture, there are 3 different simple cases, each case has two parts to be welded by spot welding, each part is clamped by the fixture and has 2 mm tolerance as shown in the picture.

Question 1: In each case, there are a few welding points(red spot) selected to be welded, some of them are geo spot, some of them are respot. In your mind, how many geo spots should be made to

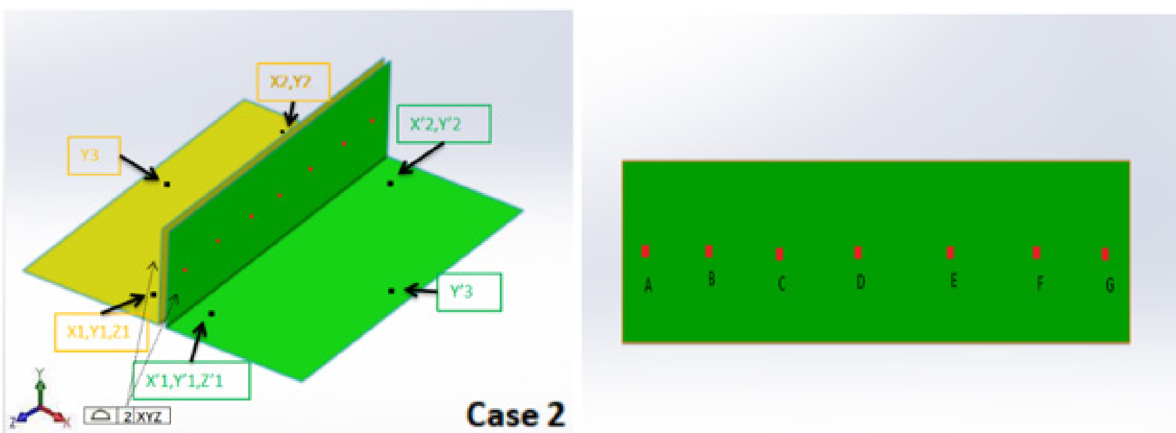
o

weld two parts together? Please write down your answers. (geo spot means the initial welding spots that are important for the geometrical outcome of the assembly, respot means the rest welding spot after geo spot welding finished)



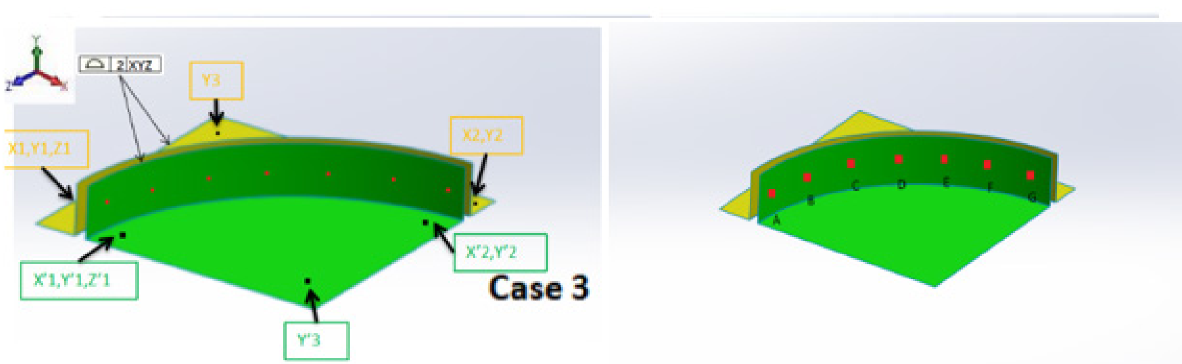
4. Number of Geo spots for case 1:

____



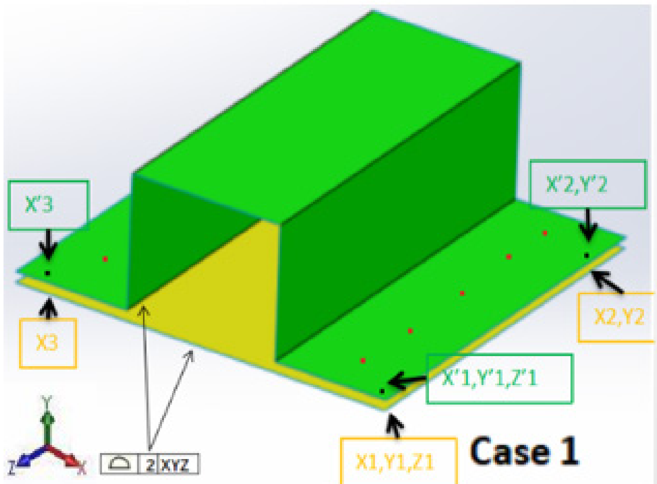
5. Number of Geo spots for case 2:

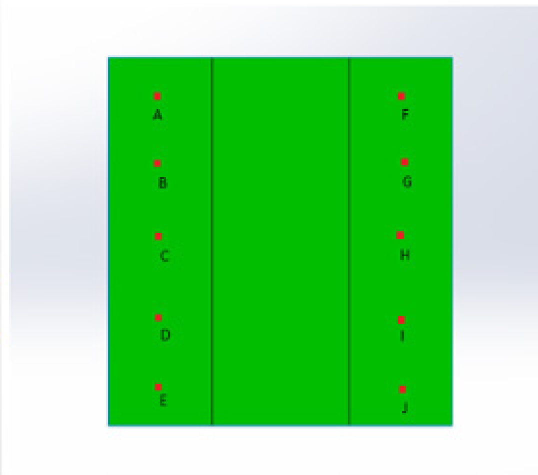
____



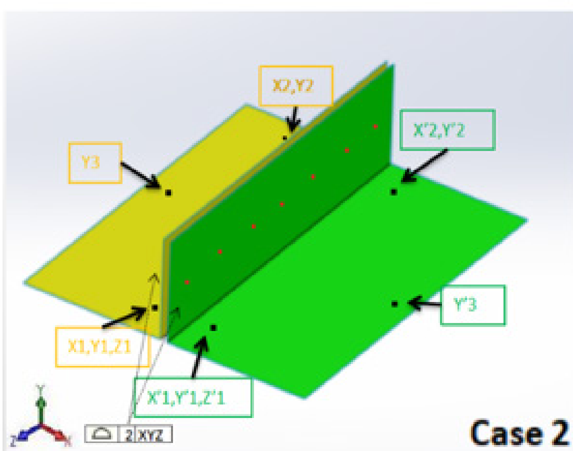
6. **Number of Geo spots for case 5:**

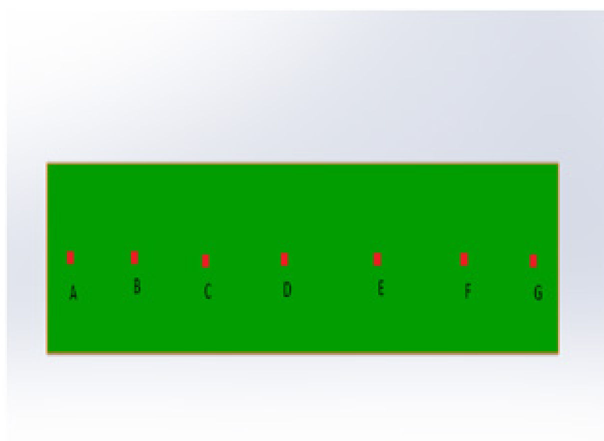
Question 2: The following pictures are the normal view(left part) & welding view(right part) of each case, there are a few welding spot options for you to select. In your opinion, which spots you want to choose as Geo spots? Please write down the corresponding spot letter. (geo spot means the initial welding spots that used to fix the target parts)



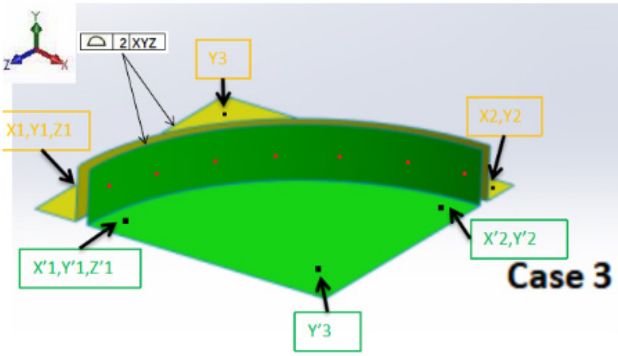


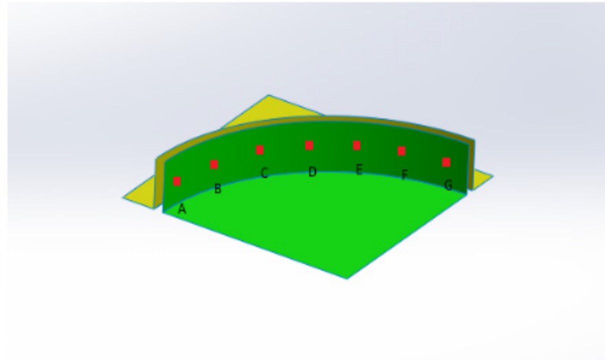
7. **Geo spot number for case 1:**





8. **Geo spot number for case 2:**





9. **Geo spot number for case 3:**

Question 3: In your opinion, how would you set the sequence of the selected geo spots for each case? Please write down the sequence with letter for each case. For example, D-A-B means the first welding point is D spot, the second one is A spot and the third one is B spot.

10. **Sequence of Geo spot for case 1:**

11. **Sequence of Geo spot for case 2:**

12. **Sequence of Geo spot for case 3:**

Question 4: Could you please explain the reason why do you choose the sequence for each case?

13. **Reason of Geo spot Sequence for case 1:**

14. **Reason of Geo spot Sequence for case 2:**

15. **Reason of Geo spot Sequence for case 3:**

In your opinion, how would you choose the importance of the following influential factors for the choice & geo spots?

16. **Fixture** *
Mark only one oval.

	1	2	3	4	5	
Low effect	⬭	⬭	⬭	⬭	⬭	High effect

17. **Thickness** *
Mark only one oval.

	1	2	3	4	5	
Low effect	⬭	⬭	⬭	⬭	⬭	High effect

18. **Distance between the geo spots** *
Mark only one oval.

	1	2	3	4	5	
Low effect	⬭	⬭	⬭	⬭	⬭	High effect

19. **Cycle time** *
Mark only one oval.

	1	2	3	4	5	
Low effect	⬭	⬭	⬭	⬭	⬭	High effect

20. **Other factor you think more important(optional):**

21. *Mark only one oval.*

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

22. **Other factor you think more important(optional):**

____

23. *Mark only one oval.*

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

In your opinion, how you would choose the importance of the following influential factors for the choice & sequence?

24. **Heat** *

Mark only one oval.

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

25. **Geo spot number** *

Mark only one oval.

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

26. **Fixture** *

Mark only one oval.

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

27. **Thickness** *

Mark only one oval.

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

28. **Other factor you think more important(optional):**

29. *Mark only one oval.*

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

30. **Other factor you think more important(optional):**

31. *Mark only one oval.*

	1	2	3	4	5	
Low effect	◯	◯	◯	◯	◯	High effect

Appendix C: The optimization process

The optimization process and results can be shown in as :

1st Iteration	SP	1	2	3	4	5	6	7	8	9
	total RMS	1.79	1.84	10.04	1.78	1.72	1.71	1.72	1.9	1.8
2nd Iteration	SP	6	1	2	3	4	5	7	8	9
	total RMS		1.88	1.86	1.69	1.74	1.71	1.76	2.03	1.76
3rd Iteration	SP	6	3	1	2	4	5	7	8	9
	total RMS			1.69	1.58	1.47	1.62	1.5	1.95	1.85
4th Iteration	SP	6	3	4	1	2	5	7	8	9
	total RMS				1.47	1.41	1.47	1.41	1.38	1.81
5th Iteration	SP	6	3	4	8	1	2	5	7	9
	total RMS					1.41	1.37	1.39	1.41	1.47
6th Iteration	SP	6	3	4	8	2	1	5	7	9
	total RMS						1.42	1.36	1.38	1.49
7th Iteration	SP	6	3	4	8	2	5	1	7	9
	total RMS							1.43	1.36	1.49
8th Iteration	SP	6	3	4	8	2	5	7	1	9
	total RMS								1.42	1.42
9th Iteration	SP	6	3	4	8	2	5	7	1	9
	total RMS									1.39

Table 11: The optimization process and results