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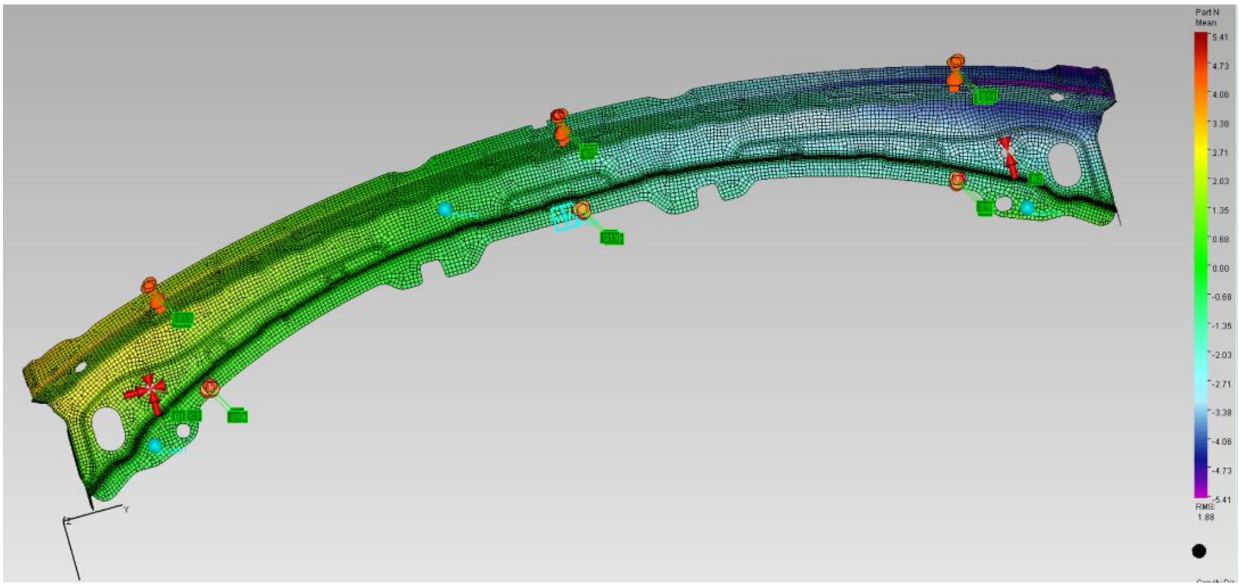

Virtual fixtures and its benefits compared with physical fixtures

Bachelor's thesis in mechanical engineering

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DEPARTMENT OF INDUSTRIAL AND
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Virtual fixtures and its benefits compared with physical fixtures

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Cover:
The final step of the Virtual Fixture process in RD&T

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Abstract

Manufacturing companies in the automotive industry have difficulties predicting deviations in their products. It is required to measure the produced parts in order to gain knowledge of the geometry outcome and to control the manufacturing processes. The sheet metal parts are assembled into a car body. Deviations in the sheet metal parts can result in problems fulfilling the set functional and esthetic requirements of the car. This means that the geometry of the sheet metal parts is important. Measurement fixtures are used when controlling if the parts fulfill their geometry requirements.

It takes time to construct, produce, and adjust the measurement fixtures before they can be used to measure sheet metal parts with accuracy. In addition, manufacturing the measurement fixtures also requires materials leading to an increased environmental impact. These fixtures are quite expensive and can only be used for a specific sheet metal part. When a new car project begins, a new set of measurement fixtures needs to be designed and produced. With car plants and suppliers spread in the world, transportation of parts and fixtures is not to be neglected, when studying the environmental impact.

An alternative to using physical measurement fixtures has been developed. The new method is called Virtual Fixture (VF). Instead of using measuring fixtures, three supports are used to hold the part while scanning the whole shape. With scan data of the part, the spheres, and the floor (the gravity plane), the change of shape due to gravity can be estimated and compensated for. You are left with a part without external forces, just as if it were in space. The model without external forces can then be placed in a virtual fixture and the clamped shape be estimated. VF-models and scan data can be sent via the internet around the world. Furthermore, the three supports can be re-used for different parts and projects. Less need for physical measurement fixtures will decrease cost and the environmental impact.

Thus, the study will consider if the measuring fixtures can be replaced with VF. Another question will also be how it will affect the economic, ecological, and social aspects when replacing the measuring fixture with the VF.

The results show that when comparing the measuring fixtures with the VF, the deviation will be approximately ± 0.2mm. VF has better repeatability compared to measuring fixtures. By using the VF, the cost will decrease and, at the same time, have a much less environmental impact.

Sammanfattning

Fabriker inom bilindustrin har svårigheter att förutspå avvikelser i deras produkter. Det krävs mätningar av producerade plåtartiklarna för att få kunskap om geometrin samt för att kontrollera tillverkningsprocesserna. Plåtartiklarna monteras ihop till en bilkaross. Avvikelser i plåtartiklarna kan resultera i problem när man skall uppfylla de uppställda funktionella och estetiska kraven på bilen. Detta betyder att geometrin på plåtartiklarna blir viktiga. För att säkerställa geometrin så används mätfixturer. Mätfixturer används för att kontrollera om plåtartiklarna uppfyller satta geomtrikrav.

Det tar tid att konstruera, producera och mäta in fixturen innan de kan användas för mätning med hög noggrannhet. När mätfixturerna produceras krävs det material som då får en påverkan på miljön. Dessutom kostar mätfixturerna en hel del och kan bara användas till en specifik plåt. När ett nytt projekt startas måste en ny uppsättning mätfixturer konstrueras och produceras. Med bilfabriker och leverantörer spridda över hela världen resulterar detta i att man inte kan försumma transporten av plåtartiklar eller fysiska fixturer när man studerar dess miljöpåverkan.

En alternativ metod till att använda fysiska fixturer har utvecklats. Den nya metoden kallas Virtual Fixture (VF). Istället för att använda sig av mätfixturer så används tre stöd som plåten vilar på medans dess form skannas. Med skanningsdatan för plåtartikeln, sfärerna och golvet (tyngdkraftsplanet), kan formändring på grund av gravitation estimeras och kompenseras för. Formen beräknas då inga yttre krafter verkar på detaljen, precis som om den vore i rymden. Den beräknade formen utan yttre krafter kan sedan placeras i en virtuell mätfixtur och den fastklämda formen kan uppskattas. VF-modeller och skanningsdata kan skickas via internet runt om i världen. Dessutom kan de tre stöden återanvändas för olika plåtartiklar och projekt. Mindre behov av fysiska fixturer kommer att minska kostnaderna och miljöpåverkan.

Därmed kommer studien behandla frågan om fysiska fixturer kan ersättas med VF. En ytterligare frågeställning är, när man övergår från en fysisk fixtur till en VF, hur det kommer att påverka den ekonomiska, ekologiska och sociala aspekten.

Utifrån resultatet kan det ses att vid användning av mätfixturer vid jämförelse med VF kommer avvikelserna att bli ungefär ± 0.2mm. Det kan även ses i resultaten att VF har bättre repeterbarhet jämfört med mätfixturer. Om man använder VF istället för fysiska fixturer så kommer kostnaderna att bli lägre och samtidigt uppnås en mindre miljöpåverkan.

Table of content

Preface

This bachelor thesis consists of 15 credit points for a bachelor's degree. It was carried out at the Chalmers University of Technology, Department of Mechanical Engineering, Institute of Industrial and Material Science. During the spring term of 2022, the thesis was conducted at half speed (50 percent).

This thesis has been carried out in collaboration with Volvo Cars, and we would like to express our deepest appreciation to Volvo Cars for being extremely accommodating and committed to this thesis. Further, we would like to thank the supervisors at Volvo Cars, Björn Lindau, Maria Andrén, and Diana Balcacian, for teaching us how to operate and analyze the results. We would also express our gratitude to our supervisor at the Chalmers University of Technology, Andreas Dagman, for helping us with the sustainability aspects.

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1 Introduction

One of the major processes in the automotive industry is the production and assembly of parts into a complete car. The variation of single parts results into variation in assemblies, thereby affecting the quality of the final product (Polini, W., & Corrado, A. (2020); Lindau et al., 2020).

According to Abdullah et al., (2003), inaccuracy in predicting the geometrical variation of the final products is a major cause of design changes or failures. Thus, the main challenge faced by many production businesses is the ability to predict geometric deviation. The geometrical deviation occurs due to physical phenomena such as thermal expansion, and deformations on the part, which will deteriorate the finished product, which is highlighted in Garaizar et al., (2016) and Corrado et al., (2017).

Today, geometric requirements set on a sheet metal part are verified by measurement of its shape whilst clamped into a physical fixture. When the part is clamped in a physical fixture, it will lock more than six Degrees Of Freedom (DOF). The applied external forces will change the shape of a non-rigid part or part assembly (Lindau et al., 2020).

Lindau et al., (2020) emphasize that using measurement fixtures to analyze geometrical tolerances have drawbacks. The reason is that when releasing the clamp, the measured part will springback due to its residual forces. Because the clamping forces are unknown, the springback data will remain unknown. According to Lindau et al, (2015), there is a need for virtual tools to be enhanced to improve the product's tolerances and reduce the time and development costs of running test series.

Physical fixtures must be designed, manufactured, and verified before use and stored nearby the place where the measurement takes place. A considerable cost in design and running production. Another method is to use simplified rigging equipment, 3D-scanning combined with finite element calculations to verify the shape of the measured part. This newly developed method will in the following be called Virtual Fixturing (VF) (Lindau et al., 2020).

Presently, there are some doubts concerning the replacement of physical fixtures with virtual fixtures. Furthermore, if the company employs the VF method, how will it benefit the company in terms of sustainability.

The physical measurement fixtures will be entitled as physical fixtures or measurement fixtures.

1.1 Background

Today, measuring sheet metal parts is made in physical fixtures with Coordinate Measurement Machines (CMM's). New physical fixtures need to be produced for each unique sheet metal part. According to Lindau et al. (2020), by placing the sheet metal part in a physical fixture the part is mostly over-constrained. This means that the clamps constrain more than six DOF´s. When clamping the sheet metal part in the physical fixture, the clamping forces will be unknown. When the clamping forces are unknown and the part is non-rigid, the information of the springback will be unknown. Due to not knowing the sheet metal parts springback, the information of the free state shape, will be lost. The free state shape is the shape of the part when it is not exposed to any external forces.

Instead of using a measurement fixture, the part can be placed on three spheres. Then, the shape of the part is scanned. As a result, a non-rigid part will be deformed due to gravity, hanging down differently depending on the chosen sphere placement. The effect of gravity can be calculated using the Finite Element Method (FEM), which together with the known shape after scanning, allows the free state shape to be established. Knowing the free state shape and having a model describing the measurement fixture, FEM calculations can be used to estimate the shape of the part clamped into a fixture. This method is called Virtual Fixturing (VF) (Lindau et al., 2020). Figure 1.1 shows the process from scanning the part, creating the estimation of the polygonal model to using the FEM calculations in the simulation tool.

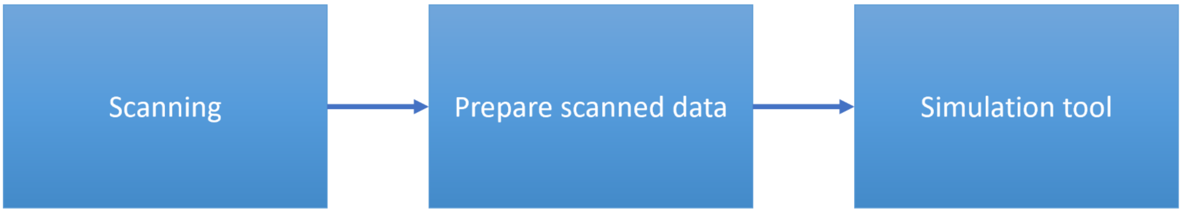


Figure 1.1: Visualization of the procedure from scanning to VF

The model describing the fixture will in the following be called VF-model. The necessary FEM calculations will be called Virtual Fixture Calculations (VFC).

1.2 Purpose and aim

The purpose is to investigate whether the VF will achieve the same accuracy in deviation compared with the physical fixtures. This is done by comparing the results from the physical fixture and the VF. The results will be illustrated as color plots which will show the deviation compared to the nominal model, describing the designed shape. In addition, it is of interest to study how much time and cost will be reduced by replacing the physical fixture with the VF. Another purpose is to look into in what way it will affect sustainability.

1.3 Delimitations

Five different sheet metal parts will be studied, see table 1.1, in a car body design. The parts will be mentioned as the letter representation instead of the name. The parts have been scanned in a physical fixture twice and using the VF three times to compare the results. The result will be shown as color plots that represents deviation between the nominal parts and the actual parts.

Representation	**Name of parts**
A	COWL LOWER
B	PANEL FRONT FLOOR LH
C	WHEELHOUSE REAR INNER LH
D	REAR FLOOR PANEL FRONT
E	TUNNEL

Table 1.1: The studied sheet metal parts

1.4 Clarification of research questions

The following research questions were formulated to assist the study:

- Can the Virtual Fixture make future predictions of geometrical deviation accurate enough to use in practice?
- Replacing the physical fixtures with the Virtual Fixtures, how will this affect the sustainability with consideration to Profit, Planet and People?

The first question will be answered by comparing the result from measuring parts clamped in measurement fixtures with the method of using Virtual Fixtures. Color plots showing the geometrical deviation will be compared to evaluate the results.

The second question, profit will be answered through interviews to collect data needed to calculate the total cost for physical fixtures. For the planet, data from interviews will be collected to calculate an environmental load value to be able to determine the environmental impact. The third aspect, people, will be determined through reasoning. For further explanation of the Profit, Planet, and People, see section 2.9.

1.5 Outline of the thesis

The theoretical framework is written in chapter 2. In chapter 3 the process of VF is described and in chapter 4 the methodology is described. The results are presented in chapter 5 and discussion in chapter 6. The conclusion and future work are covered in Chapter 7.

2 Theoretical framework
In this section, the previous research is presented.

2.1 Product development
Traditional product development at a company is based on a problem-solving process. The steps in the problem-solving process are shown in figure 2.1. The first step is to formulate the problem. Here the problem will be answered from different interviews and can be difficult to concretize. From the formulated problem this is translated into criteria that are possible to measure. Step three is searching for solutions. The idea is to try to come up with as many solutions as possible. The solutions are evaluated from the problem and criteria and the best solution is chosen. The last step is to develop the solution (Johannesson et al., 2013).

Figure 2.1: The steps used in product development (translated from swedish to english) (Johannesson et al., 2013)

2.2 Geometry assurance
Geometry assurance uses a series of activities where the purpose is to reduce the repercussion of the geometric variation when the product is complete. The activities will occur in different stages of the product realization loop. The process can be divided into three phases, which are the concept phase, verification, and production phase (Söderberg et al., 2016), see figure 2.2.

The first phase is called the concept phase. This phase involves the development of products and production concepts. Various concepts (sub-solutions) are analyzed, optimized, and tested virtually based on available manufacturing data to assure their ability to withstand manufacturing variation. This phase involves optimizing concepts for robustness and verifying them with a statistical analysis of tolerances (Söderberg et al., 2016).

The production system, as well as the product, are tested during the verification phase. This phase involves inspecting and preparing off-line programming with Coordinate Measuring Machines (CMM´s) and scanning equipment as well as verifying the physical properties of the product and production system. Additionally, the inspection routines and strategies are decided during this phase (Söderberg et al., 2016).

The last phase is the production phase. All adjustments to the production process have been completed at this point, and the product is fully produced. This phase involves controlling, identifying, and correcting production errors based on inspection data (Söderberg et al., 2016).

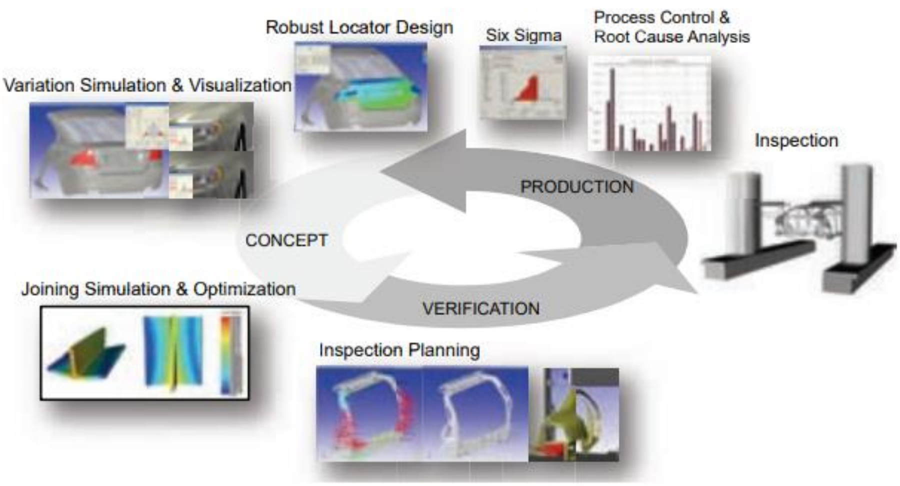


Figure 2.2: Visualization of the production realization loop (Söderberg et al., 2016)

2.3 Positioning system using 3-2-1 method

A 3-2-1 positioning system can be used to unequivocally determine a part and achieve good repeatability when positioning it. This system will use six points, known as references, to lock the parts in six degrees of freedom. By securing the parts six degrees of freedom the part will lock three translations and three rotations. In the first direction, three points, A1, A2, and A3 are essential. This creates a plane that will lock in one translation and two rotations, see figure 2.5. The following two points, B1 and B2 are 90 degrees off the plane, forming a line that locks one translation and one rotation. By setting the last point, C1 90 degrees from both the plane and the line, a 3-2-1 positioning system is created and all six degrees of freedom are locked (Söderberg & Lindkvist, 1999).

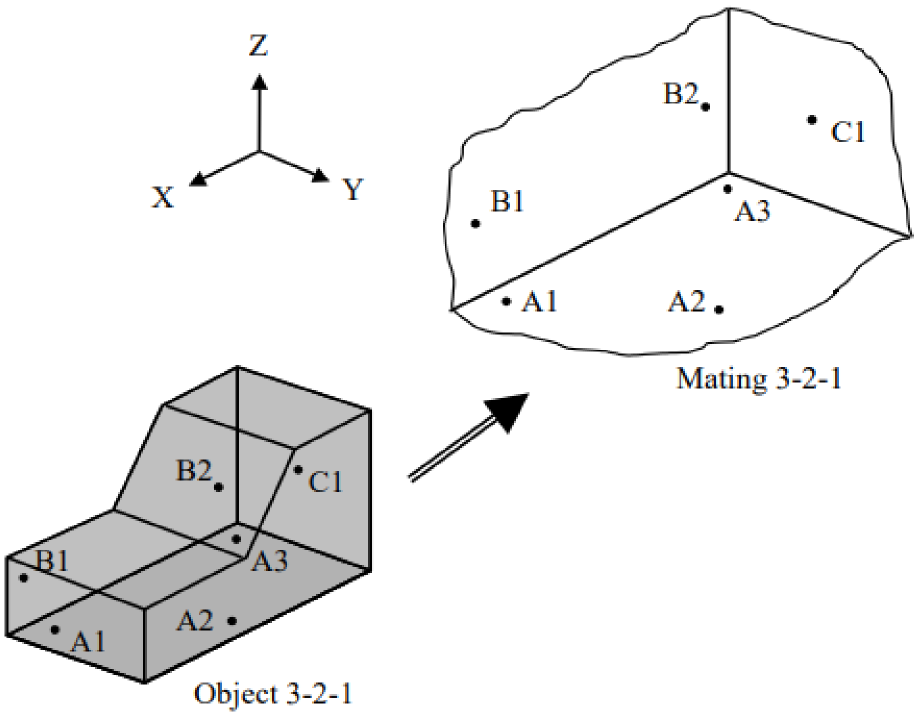


Figure 2.5: 3-2-1 positioning system (Söderberg & Lindkvist, 1999)

2.3.1 Locators and properties for holes and slots

In most cases not only surfaces are used to lock parts into place. Commonly used features are circles and slots. Circles are used with a pin in the hole to steer the part in two or three directions. When the circle steers in two directions it can only steer in the directions which is not the normal plane direction. When the circle steers in three directions, the position is locked. For the hole to steer in three directions the hole need support from the normal plane it is located on. A slot can steer in one or two directions. It can only steer in the direction where the slot is smallest and cannot steer in the direction where the pin can glide in. To steer the slot in two directions the slot needs to have support from the normal plane (Rezaei et al., 2020).

2.4 Tolerance and variation analysis on sheet metal part

Tolerance analysis consists of two sub-categories. The first category is to describe methods that are used to determine the tolerance specifications. The second category, which is commonly called tolerance stackup, is to define the variation between at least two features (Fischer, 2011).

Tolerance specifications is used to understand the drawing of the model, which includes the tolerances and dimensions. The tolerance stackup is used to analyze the gaps or distances between features that are not dimensioned directly. As an example, the pin must be able to fit into the hole (Fischer, 2011).

Tolerance analysis and variations of each component are taken into account to verify that a design is functional (Chase & Parkinson, 1991).

Rigid analysis is defined as the part not being over-constrained when defining or making assumptions about the locators. In the case of a non-rigid analysis, the part may bend or be deformed during positioning, resulting in an over-constrained locating system. Therefore, when doing the compliant analysis, the stiffness of the sheet metal part and the clamping forces will be included when predicting the robustness and variation (Wärmefjord et al., 2008).

Variation analysis, along with other simulation methods such as stability analysis and contribution analysis, is used for evaluating positioning systems and distributing tolerances. These analyses are used to study the robustness of the chosen design (Söderberg & Lindkvist, 1999; Wärmefjord et al., 2008).

Variation analyses are commonly based on Direct Monte Carlo (DMC) simulations. Using this method, one can determine the distribution of a critical measure (Wärmefjord et al., 2008).

The above methods are often referred to as Computer Aided Tolerance analysis. RD&T (Robust Design and Tolerancing) is an example of such a tool (RD&T Technology, 2021). RD&T also includes a Finite Element Method-solver (FEM-solver). This makes it possible to study the behavior of non-rigid parts when positioned in an over constrained fixture.

2.5 Measuring methods

Measurements are made to control set geometric requirements on the produced part, sub-assembly, or car body. Firstly, an alignment is made with features that are used to let the machine (CMM or scanning equipment) know where the part is in space using the 3-2-1 positioning system. After this, features such as e.g. holes, slots, edges, and surface points can be measured and compared with the nominal model. The result will be a deviation between the nominal features and the measured features.

2.5.1 Using CMM as a measuring method

CMMs are used to measure physical parts and use a probe to take points. The probe will make contact with the part and retract a short distance before moving on to the next point. To use the CMM one can either create Off-Line Programs (OLP) or simply create programs while measuring a part (Legge, 1996).

2.5.2 Using scanning as a measuring method

3D scanning is used to analyze the shape deviation in parts. A scanner is used to send out a laser light which reflects differently depending on how far away the part is and builds up a point cloud. Figure 2.3 shows an example of a scanner that can be used. The scanner will not touch the part which is useful if the part is non-rigid. A 3D analyzing program such as Polyworks (Innovmetric, 2022) is used to collect the point cloud and create a polygonal model. Figure 2.4 shows a polygonal model and is built up of small triangles. From the model, one can measure features such as circles or slots and compare them with where they are supposed to be from the nominal model (see figure 2.5). The main features, also called Master Locating Points (MLP:s), are used to position the scanned part to the nominal part to analyze the deviation.

Figure 2.3: An example of a scanner that can be used, with an iPhone X as reference

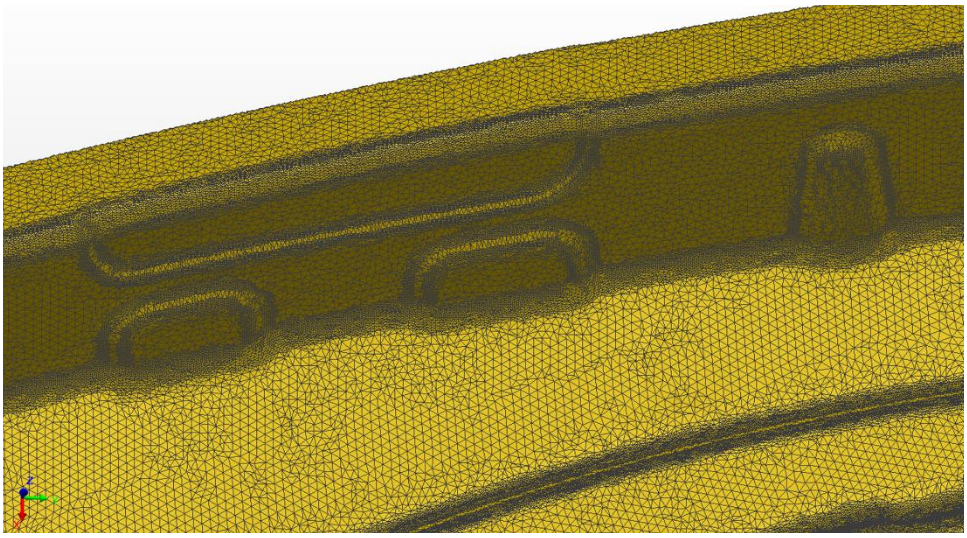


Figure 2.4: A polygonal model in Polyworks

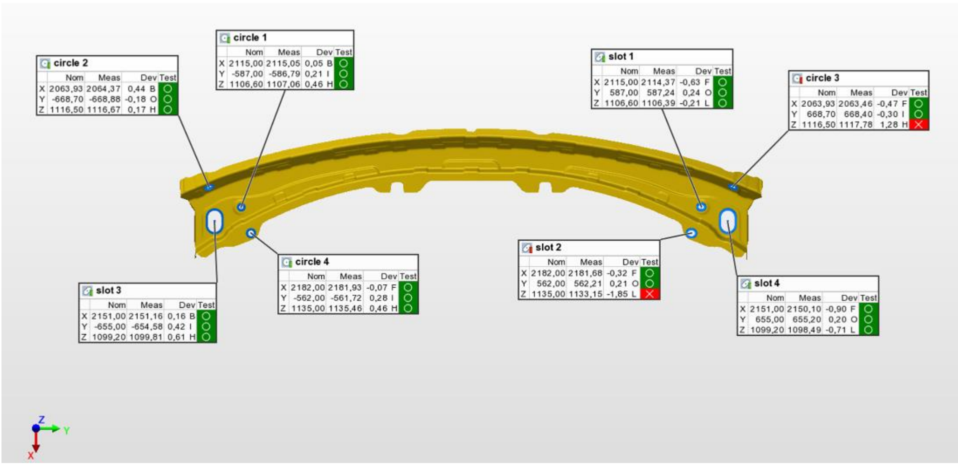


Figure 2.5: Measured features, circles and slots, that are compared to nominal in Polyworks

2.5.3 Comparison between the two measurement methods

When comparing scanning to CMM, scanning will acquire the shape of the whole part, whereas the CMM shows only the deviation in the discrete points measured. CMM is therefore often used to collect statistical data for production steering. Full scanning of part shapes is used more for deeper analysis.

2.6 Physical fixtures

Today measurements of sheet metal parts are made in measurement fixtures which are made to hold the part while measuring. A simple version of a physical fixture is shown in figure 2.6. The fixture uses the MLP (Master Location Points) to align the part which is six points in the 3-2-1 method described in section 2.3. The picture to the left in figure 2.6 shows the plane, the middle picture shows when the line is added with two points and the picture to the right shows when the last point is added.

When using the measurement fixtures, there are often more clamps than required. It is advantageous to use all clamps because it gives the sheet metal part extra support, but the disadvantage is that it will be over-constrained. Figure 2.7 shows a fixture made for a single sheet metal part. Another example of fixture design is shown in figure 2.8. This fixture has two pins and six clamps. The left pin fits in a circle while the right hole fits in a slot hole. When using more than six steerings, the fixture is over-constrained which changes the shape when the clamps are closed. With the data from the parts in the fixture, it is impossible to calculate how the part will springback when released from the fixture because there is no information about the reaction forces in each clamp or pin. A solution can be to create fixtures with sensors measuring how much force is applied, but this would make the fixtures too complicated and probably more expensive (Lindau et al., 2020).

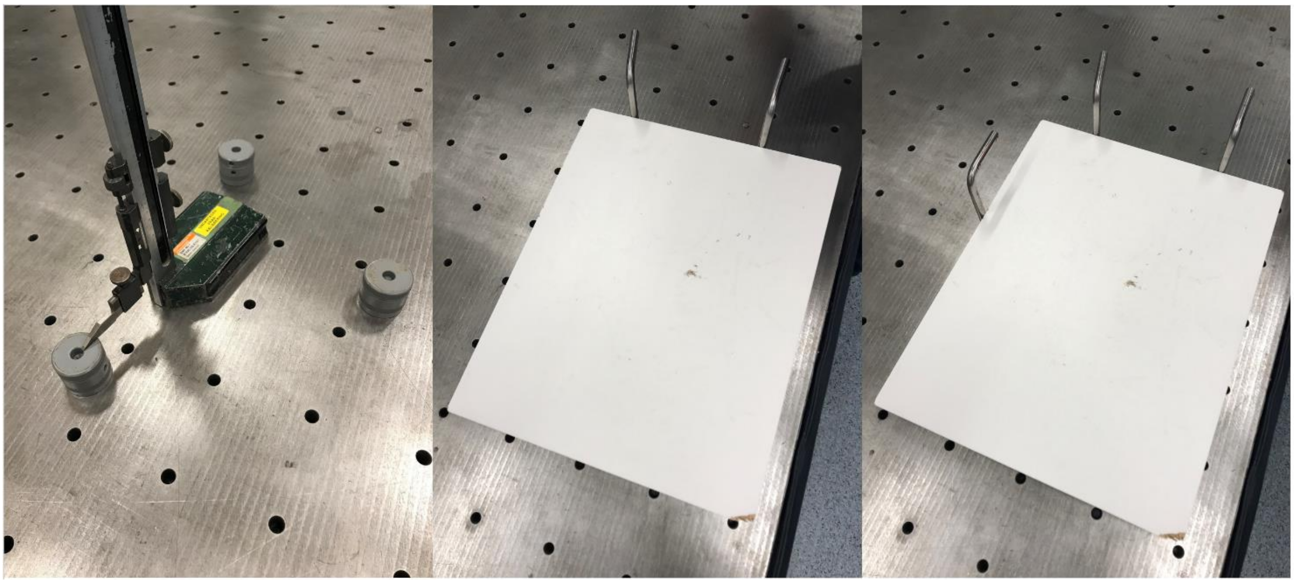


Figure 2.6: A simple version of a physical fixture

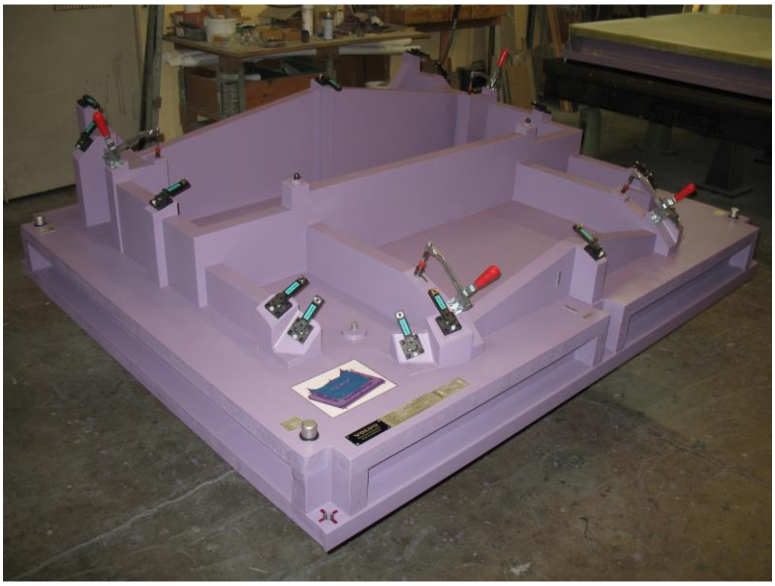


Figure 2.7: A physical measurement fixture made for single sheet metal parts

Figure 2.8: A physical measurement fixture for subassemblies with a sheet metal part

2.7 Virtual Fixture method

A solution for measuring a part using a "three-point setup," which is the base for a Virtual Fixture (VF), can be used to estimate the shape of the clamped part. The springback information loss that occurs due to physical clamping forces is not lost when using a 3-point setup (Lindau et al., 2020).

2.7.1 Hanging parts and calculate with g-force

The free state must be known to be able to perform virtual assembly analysis. The free state is a part that has no external forces acting on it as if it was in space. A way to come close to a free state is to hang the part to minimize bending and twisting of the part due to gravity and other external forces, see figure 2.9 (Lindau et al., 2020). This method has limitations depending upon the size and shape of the part. Curved shapes can be hard to hang in a direction without gravity influencing the shape. Large details can be hard to cover with the scanning tool due to e.g. measurement arm access.

Figure 2.9: Hanging a sheet metal part to reduce g-force

2.7.2 Scanning with three locators, represented as spheres

Another way to eliminate external forces is to put the part on three spheres acting as locators (see figure 2.10). The part is scanned, along with scanning the floor and the spheres to reverse calculate the gravity. With this data, it is possible to virtually put the part in the VF and simulate the clamps (Lindau et al., 2020). The process is described thoroughly in section 4.

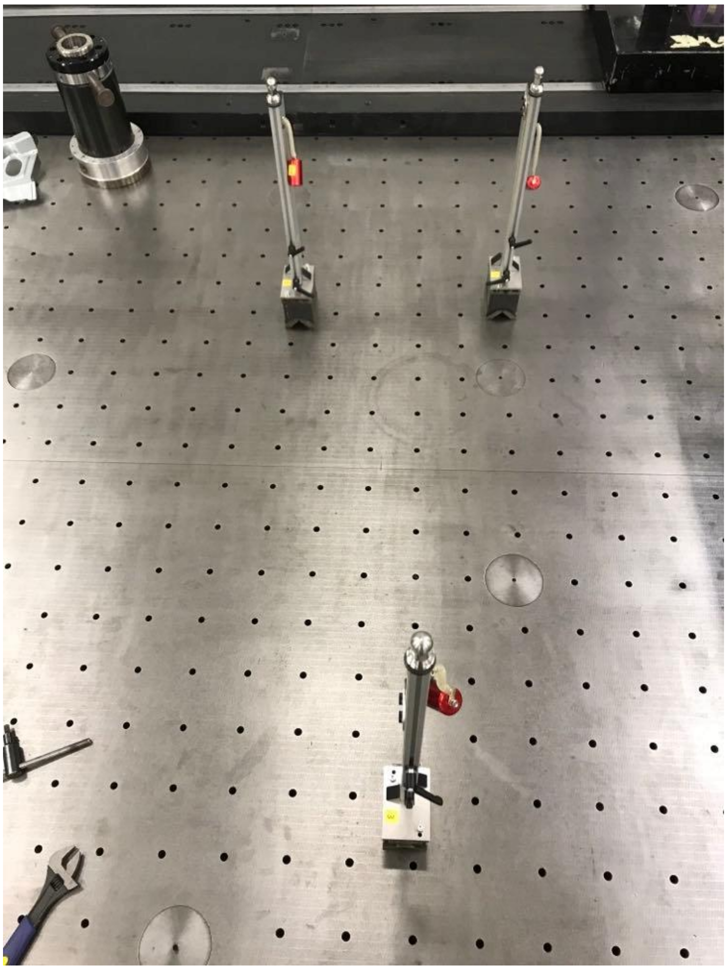


Figure 2.10: Three spheres positioned to scan a part

2.8 Sustainability methods

Sustainability is a core aspect of today's product realization processes. There are numerous ways to approach this from both theoretical and practical points of view. The most common one is TBLM (Triple Bottom Line Model) which evaluates sustainability. The environmental aspects of the TBLM can be approached by using LCIA (Life Cycle Impact Assessment) (Mattioda et al., 2014).

2.8.1 Triple Bottom Line description

Looking a while back, companies were only interested in making money and earning profit, but lately two other aspects have been more important, namely the people and the planet. Together these three key words also called the "three Ps" represent the Triple Bottom Line Model (Elkington, 1997), see figure 2.11. The first P, profit, is about cutting costs and increasing income. The second P, people, is focused on employees who are the most valuable asset for a company but also people around the company like suppliers and customers. The third P, planet, is focusing on the environment and how not to jeopardize the resources in the world. All three must collaborate to create the most sustainable environment (Dalibozhko & Krakovetskaya, 2018).

Figure 2.11: Triple bottom line model (Dalibozhko, A., & Krakovetskaya, I., 2018)

2.8.2 LCIA used to evaluate physical fixtures

The Life Cycle Impact Assessment (LCIA) method is used to assess the environmental impact and resource release of natural resources. The LCIA is based on the Life Cycle Inventory (LCI). LCI consists of a quantity of data about the use of natural resources and emissions to the environment. An LCIA provides insights into the correlation between environmental pollution, human health issues, and resource depletion caused by products and processes (Curran, 2012).

2.8.3 EPS used to calculate a numerical value on environmental impact using physical fixtures

The Environmental Priority Strategies (EPS) is one method used for calculating the product's environmental impact. The outcome from the EPS is a numerical value where the unit will be Environmental Load Unit (ELU). The ELU is calculated by multiplying a material specific index (Environmental Load Index) with the quantity of the material. The Environmental Load Index is a pre calculated value which represents for example the production for a certain material. The Environmental Load Value (with the unit ELU) will indicate the environmental impact which can be i.e., pollutant emissions, waste generation, and the use of a specific material (Jansson-Liljenroth, 1994).

3 The process of Virtual Fixture

In this section, the process of the Virtual Fixture (VF) is reported.

3.1 Preparing for the Virtual Fixture Calculation

A VF consists of two parts. The first part is the VF-model, and the second part is the Virtual Fixture Calculations (VFC) (see figure 3.1). The VFC will be further described in section 3.1.3. To create the VF-model, two files are required. The first file is a JT-file which holds the nominal model and Product and Manufacturing Information (PMI) (see figure 3.2). The PMI has information about the positioning reference, i.e. the fixtures pins and clamps. The other file needed is a mesh file that is used to describe the stiffness of the part.

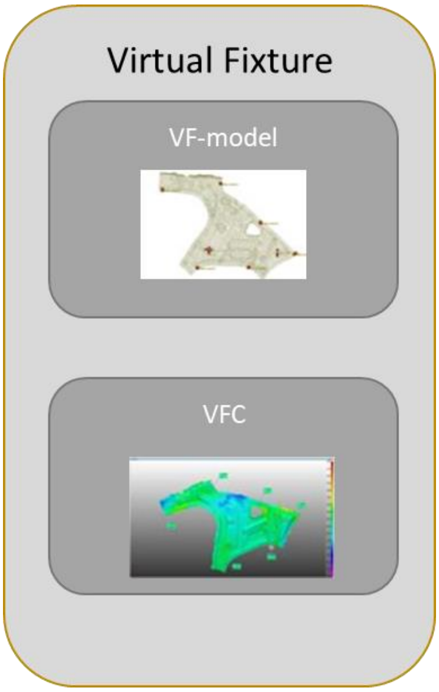


Figure 3.1: The parts that are included in the VF

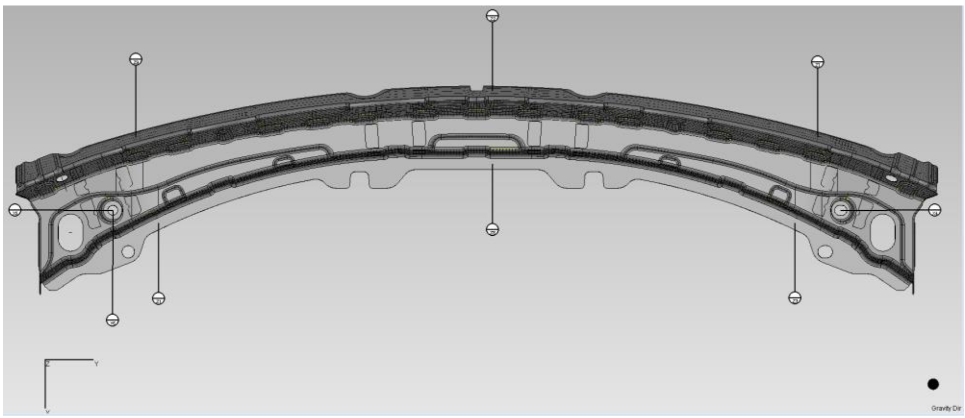


Figure 3.2: PMI for sheet metal part A

The files are imported to the RD&T software. The next step is to choose where the spheres are placed on the part. It is important to position the spheres so that the surfaces they are positioned at are having the same direction. If the surfaces do not have the same direction the part might not lie stable. Figure 3.2 shows the part where the spheres are positioned. The same color indicates that the surfaces have the same direction. In figure 3.3, the red circles mark chosen sphere's placement and the yellow the center of mass. The center of mass needs to be inside the black triangle built up by the three spheres (otherwise the part will fall off).

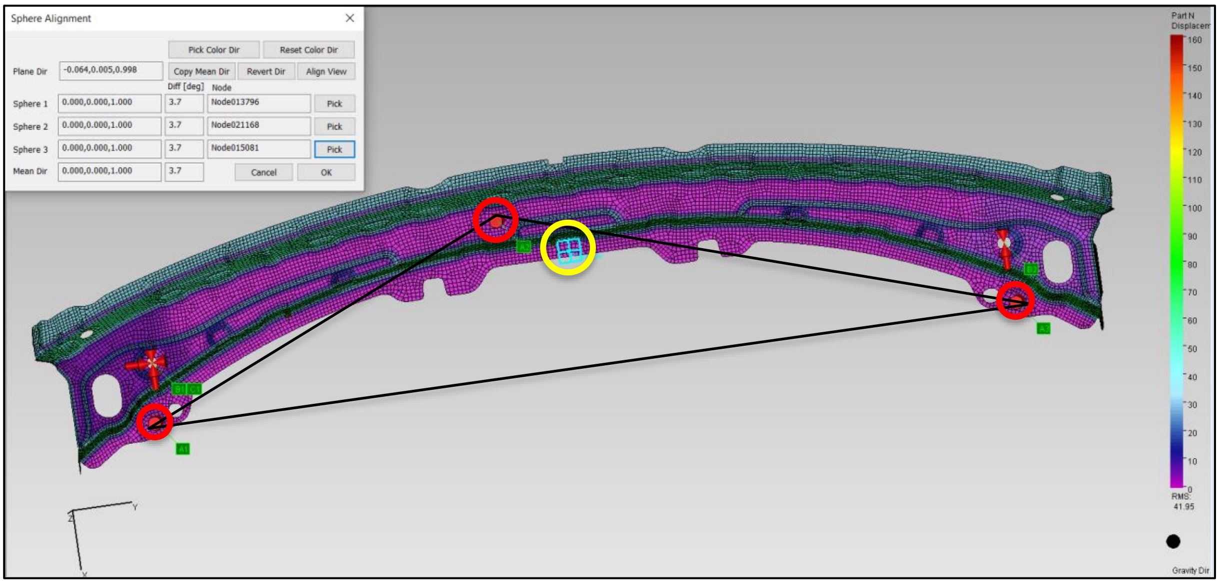


Figure 3.3: Positioning spheres to create VF –model

The sphere placement is recalculated to how the spheres should be positioned in comparison to each other, see figure 3.4. The spheres are positioned on the base plate according to the coordinates in figure 3.4 on the lower right corner. The first sphere has got the coordinates 0 in X, Y, and Z, and the other spheres are positioned in relation to the first sphere.

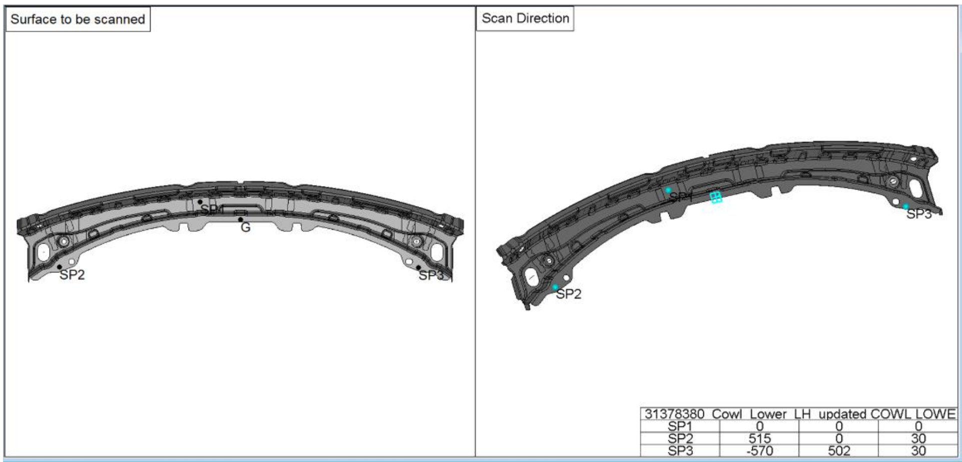


Figure 3.4: Position of the spheres relatively

When this is made the VF-model is finished with spheres, pins and clamps, see figure 3.5. In the blue circle, there are four red arrows pointing in two directions which indicates that the feature will steer in two directions. Here a pin in a circle is used. In the orange circle there are instead two red arrows pointing in one direction. The direction the arrows point is the direction which the feature is steered which means that a pin in a slot is used. In the white circles there are arrows normal to the direction of the surfaces and these are clamps.

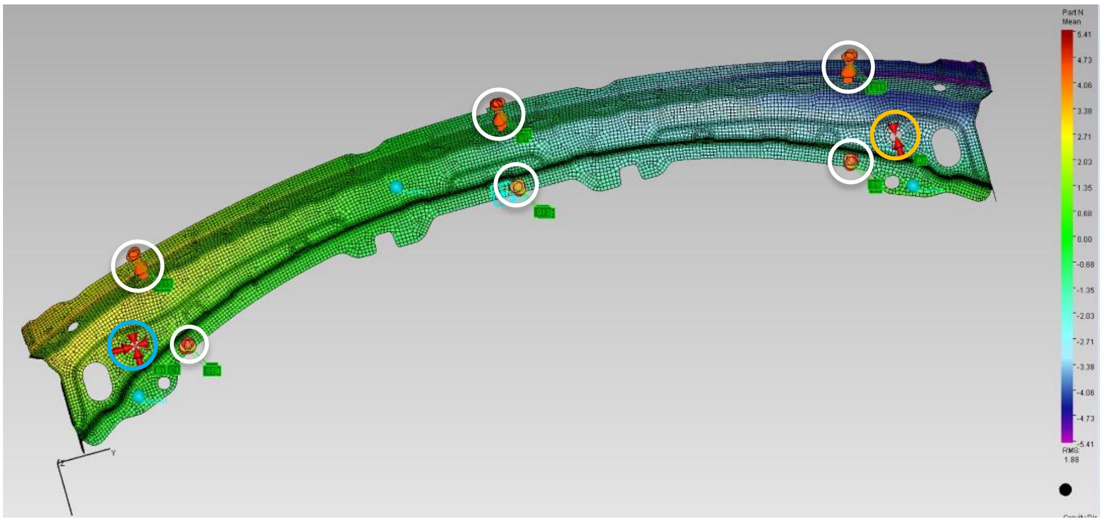


Figure 3.5: VF-model

3.2 Scanning for the Virtual Fixture

First, the spheres are positioned on the baseplate, shown in the first picture (A) of figure 3.6. Their position is determined by the preparation calculations of the VF, see figure 3.4. After this, scanning on the sheet metal part is made, shown in the second picture (B) of figure 3.6. The last 2 pictures (C, and D) in figure 3.6 show the scanning of the spheres and baseplate. This is scanned to be able to calculate how the part is held up and in what direction the g-force is pointing.

Figure 3.6: The process of scanning for the VFC

When the scanning is made the polygonal model is created. All circles, slots, and rectangles features are extracted from the nominal model and measured on the polygonal model. A plane feature is created on the scanned plane and the sphere features for the three spheres are created. The scanned polygonal model is exported together with all the features (see figure 3.7).

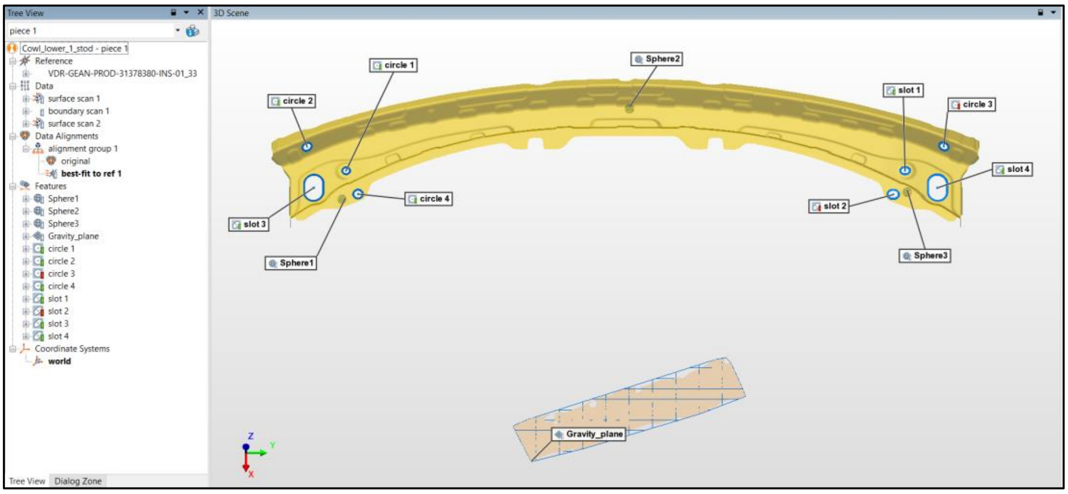


Figure 3.7: sheet metal part A with features

3.3 Virtual Fixture Calculations in RD&T

The exported model and features are imported to the VF-model, and the VFC are made. Estimations are made for two different scenarios. The first shows the sheet metal part if it would be put in a fixture (see figure 3.8) and the other in free state, without forces acting on the part (see figure 3.9). With the result it is possible to judge if the part is outside of tolerance and if so, report to suppliers asking for possible corrections in their tools.

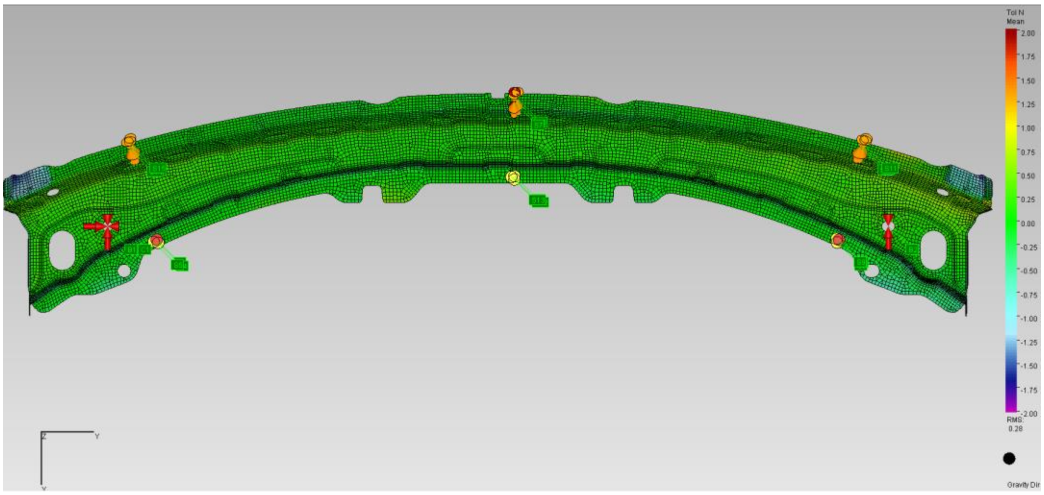


Figure 3.8: Sheet metal part A in a VF

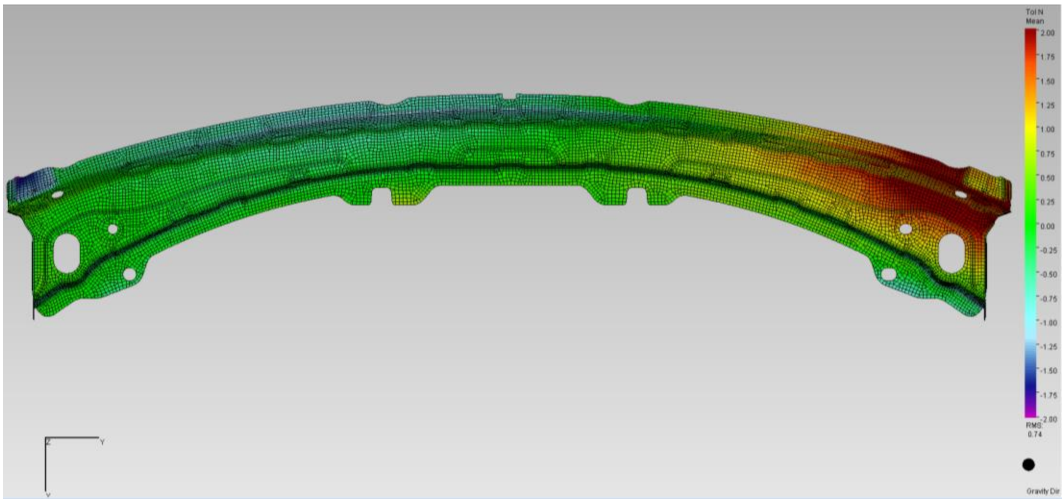


Figure 3.9: Sheet metal part A in free state

3.4 The difference between physical fixture and Virtual Fixture process

When putting a sheet metal part in a physical fixture the part will be clamped and over-constrained which leads to changing the form of the part. Furthermore, the part's tendency to springback is lost as the clamping forces are unknown.

When the part instead is put on the three spheres it will hang differently. The first step in the VFC is to make reverse FEM calculations, to get a model of the part without the gravity effect. This is possible by knowing the sphere's position and which direction the gravity plane (the plane that the spheres are standing on) has. The next step in the calculations is to put the calculated model into the VF with the PMI, where the pins and clamps are defined. This gives the results of three different setups; on spheres, without gravity effect, and the part in a fixture not losing the information about the measured part's tendency to springback.

4 Methodology

To answer the first research question, accuracy tests have been performed, comparing results using physical fixtures and the Virtual Fixture (VF) method. Addressing the second research question, the Triple Bottom Line Model (TBLM) has been adopted to study cost savings, human and sustainability effects.

4.1 Methodology used to gather data for geometrical aspect and the environmental impact

The approach of gathering data of color plots showing geometrical deviation can be sub-divided into 4 parts, see figure 4.1.

1. The first step was to comprehend and educate the project members on the current systems.
2. The second step involved conducting a pilot study of the process from scanning a sheet metal part to acquire color plots showing geometrical deviation, with the goal of establishing work procedures.
3. The next step includes two parts. The first is to proceed with the Virtual Fixture Calculations (VFC) and carrying out interviews to acquire material data needed for the Environmental Priority Strategies (EPS). The last step also includes calculation of total cost for the physical fixtures.
4. Finally, the data from the VFC and the result from the interviews are analyzed with the aim to study if the VF-method works in practice and if it is a better choice for the environment.

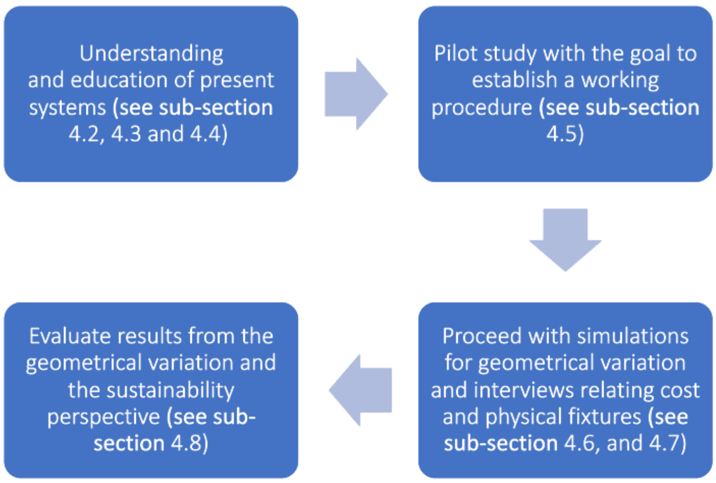


Figure 4.1: Flow chart of the method

4.2 Understanding the given case

The first thing that was investigated was the usefulness of VF. Then, from the color plots showing geometrical deviation, judge if the accuracy from the VF is feasible to use in practice. Lastly, calculating the savings in costs and sustainability using VF.

4.3 Education and training in different areas

Below, there is a bullet list in chronological order that sum up the different areas that were required.

We were educated and trained:

- To understand 3-2-1 positioning system and six degrees of freedom generally.
- To understand differences between a constrained and an over-constrained positioning system.
- To use the 3D-scanning system and the measurement program Polyworks.
- To understand basic functionality of the RD&T simulation tool.

- How to create a VF in the variation simulation tool RD&T.
- How to extract necessary data from Polyworks, which is needed for the VFC.
- And finally, how to analyze the measurement results to draw a conclusion.

With this as a foundation, we went on to the next phase.

4.4 Approach for theoretical framework and introduction using literature review

A literature review serves as a comprehensive review of existing knowledge about the subject or theme which will be the basis (Bell et al., 2019) for the introduction and the theoretical framework. Therefore, a literature review has been conducted. The literature review is in the form of a narrative review. A narrative review provides the researcher with an overview of what is already known in an area and intends to introduce a researcher's own research into the area (Bell et al., 2019). The introduction is written to provide an overview of the problem with the measurement fixtures. The theoretical framework includes the information needed to understand measurement fixtures, including the benefits and advantages of applying VF.

4.5 Pilot study with the aim to utilize the education and training

After some basic training, the achieved knowledge was used on a first test case in Pilot Plant measurement room at Volvo Cars Gothenburg. The aim was to improve the skills before performing tests in factory environment at the Volvo Cars Torslanda plant.

In this phase, also questions for interviews were prepared, targeting sustainability aspects related to the use of measurement fixtures.

4.6 Proceed with simulations for geometrical deviation

Five sheet metal parts belonging to the floor of the car has been studied. The chosen parts are colored in figure 4.2. In order to acquire data for color plots showing deviation, scanning of the sheet metal parts is required.

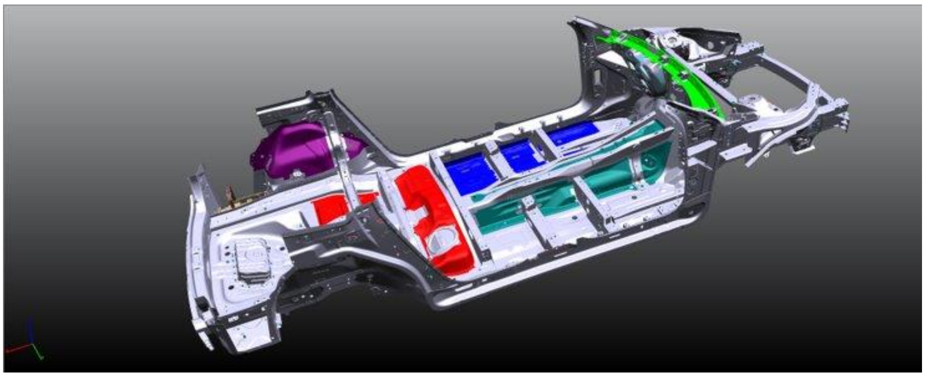


Figure 4.2: The colored parts are the five test cases that have been studied.

The following steps were performed when scanning the sheet metal part in the fixture:

1. The sheet metal part is placed in the physical fixture.
2. Fasten the clamps in the prescribed order.
3. Scan the part.
4. Release all clamps.
5. Lift the sheet metal part out of fixture.
6. Repeat again for the second time.

The scanning is carried out twice to verify the measurement method.

When placing the sheet metal part on three spheres, it can behave (hang down) differently. Therefore, the scanning was repeated three times to study the repeatability.

When scanning the sheet metal part using three spheres, it was done in the following order:

- Position the three spheres according to the layout on the base plate (see figure 3.4).
- Place the sheet metal part on the three spheres according to the layout.
- Scan the part.
- Take away the part.
- Scan the spheres and baseplate.
- Repeat it three times.

4.7 Interviews relating to cost and physical fixtures

From the interviews, data were acquired regarding the environmental impact and cost. The interviewees working as equipment engineers provided data needed for the EPS. From the data, calculations for the environmental impact will be used to evaluate the environmental impact when comparing the physical fixture with the VF. In addition, it was also provided cost for the physical fixture with different weights. Therefore, total costs for physical fixtures could be calculated.

4.8 Quantitative method and qualitative method with the aim to acquire data

A quantitative method defines techniques and methods that are more relevant when collecting and analyzing data (Merriam et al., 2015). The data was acquired by comparing the deviation measured using a physical fixture with the estimations made by the VF. Therefore, the qualitative method, which requires collecting and analyzing data, was more suitable.

The qualitative method will also be employed. The reason for this is to gain a more in-depth understanding of the subject from the participants based on their experiences and attitudes (Dawson, 2007). Therefore, a semi-structured interview will be conducted.

In a semi-structured interview, the researcher has a list of topics that will be covered, usually referred to as an interview guide, and questions will be asked in a given order. To compare the results of interviews, the researcher needs to gather specific information. As a result, each participant must be asked the same questions. If the interviewer refers to something the respondents said, follow-up questions can be added to the interview guide (Bell et al., 2019). It keeps the interview more flexible, because it leads to specific answers (Dawson, 2007).

The interviews took place at either Microsoft Teams or a predetermined location, where they lasted around 30 minutes. The first questions were designed to gather information about the interviewees' backgrounds and areas of expertise. Following that, questions about the topic were presented. In addition, if necessary, follow-up questions were asked to gain a more in-depth understanding of the subject. The interview that was conducted using Microsoft Teams was transcribed live to avoid missing any crucial information from the respondent. The interviews, which were conducted at a predetermined location, were summarized based on physical demonstrations and examples given to demonstrate the respondent's answers to the questions.

4.9 Evaluation of results from the geometrical deviation of a part

The results will be presented by color plots showing the geometrical deviation for each sheet metal part. We have analyzed the following:

- Color plots showing deviation from nominal of a part when fixated in its physical measurement fixture.
- Color plots showing deviation of a part using the VF-estimation.
- A direct comparison of results obtained using a physical/measurement fixture with VF-estimation.

- Deep analysis of the fixture measurements studying the part deviation in close premises to the clamps. The measurement fixture itself is not nominal and these faults will influence the measured shape. The VF-estimation, however, models a nominal fixture. This fact is important to consider when comparing the fixture results with the estimated ones.
- Modification of the VF-model, to also include the clamping faults detected in the previous point.
- New comparison of results obtained using a measurement fixture with estimation made by modified VF-model.
- Differences between the two results obtained measuring the part clamped in fixture.
- Differences between the results obtained using the VF-method.

4.10 The EPS method has been used in terms of ecological aspects of sustainability

The required material data was obtained from the Swedish Life Cycle Center (Swedish Life Cycle Center, 2022). A numerical value with the unit ELU/kg has been calculated based on the material data. Then, the VF and the physical fixture are evaluated to see the differences between the numerical value in ELU/kg.

5 Results

In this section the results are presented and how to understand the color plots.

5.1 Results from the Virtual Fixture Calculations

In chapter 4.8 we described the different kind of analysis we have performed in order to answer the first research question:

- Can the Virtual Fixture make future predictions of geometrical deviation accurate enough to use in practice?

A vital part in our analysis is the interpretation of the color plots showing the deviations from nominal shape or other reference shapes.

The results will be shown with help from a color scale which represents the level of deviation from nominal for each part. The color scale reaches from red to green and then to blue. A simple figure shows how the color scale works, see figure 5.1. In the figure, the black horizontal line is the nominal model (or other reference chosen as target), and the arrow shows from where the scanning is made. The red part means that the analyzed part is above the nominal part. The blue part means that the scanned part is under the nominal. When the part is green it means that the scanning is close to the nominal part. Note that if the part would be scanned from the other side of the drawn line, it is the opposite compared to the scanner, this is illustrated in figure 5.2.

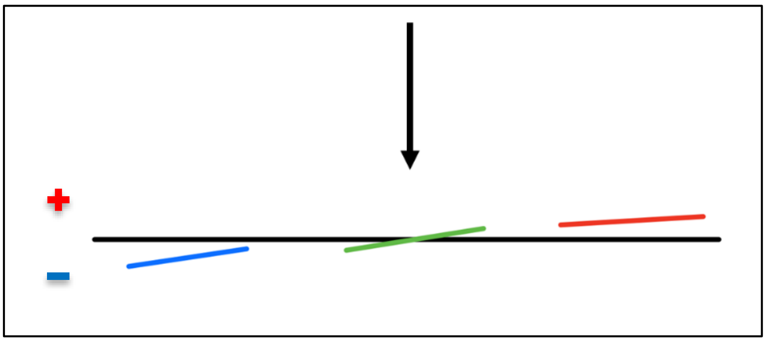


Figure 5.1: A simple figure on how the color scale describes the geometrical deviation from nominal

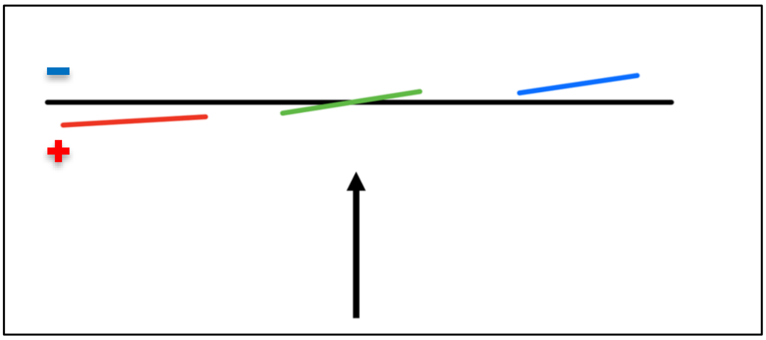


Figure 5.2: A simple figure on how the color scale works but scanned from other direction.

The sheet metal part A will be presented in detail in this result section. The rest of the studied cases will be presented in the appendix A-D.

Figure 5.3 shows the differences between the physical fixtures and the nominal model. Figure 5.4 shows the deviation between the estimated shape from VF with the nominal model. The color plots have the same scale, and the two plots looks similar. Comparing the points taken in the figures they do not deviate more than 0.2 mm.

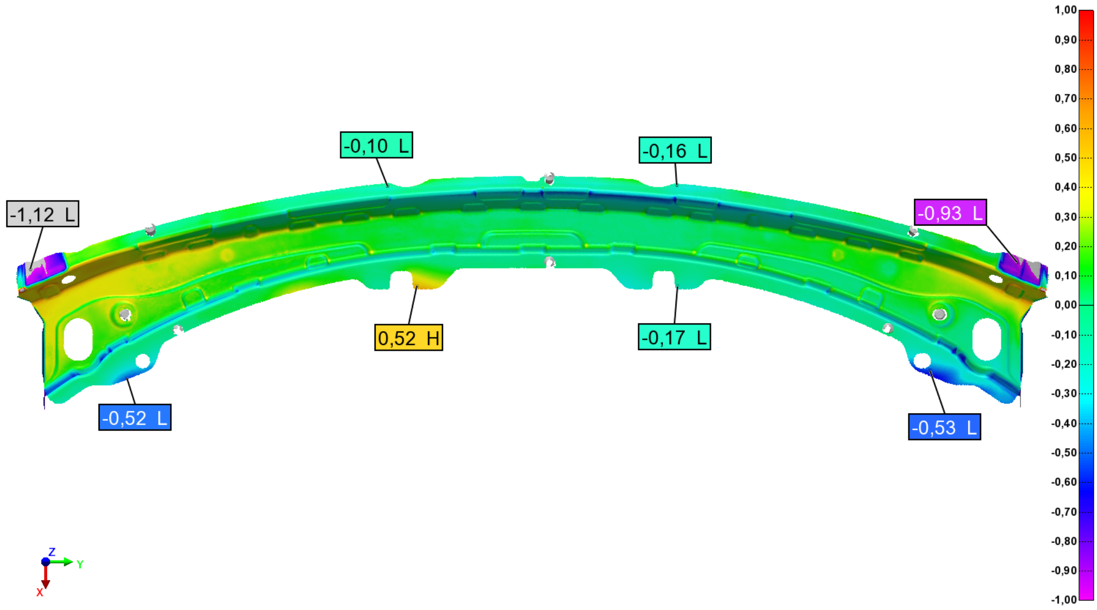


Figure 5.3: The first analysis, comparing the scanning in the physical fixture with the nominal model.

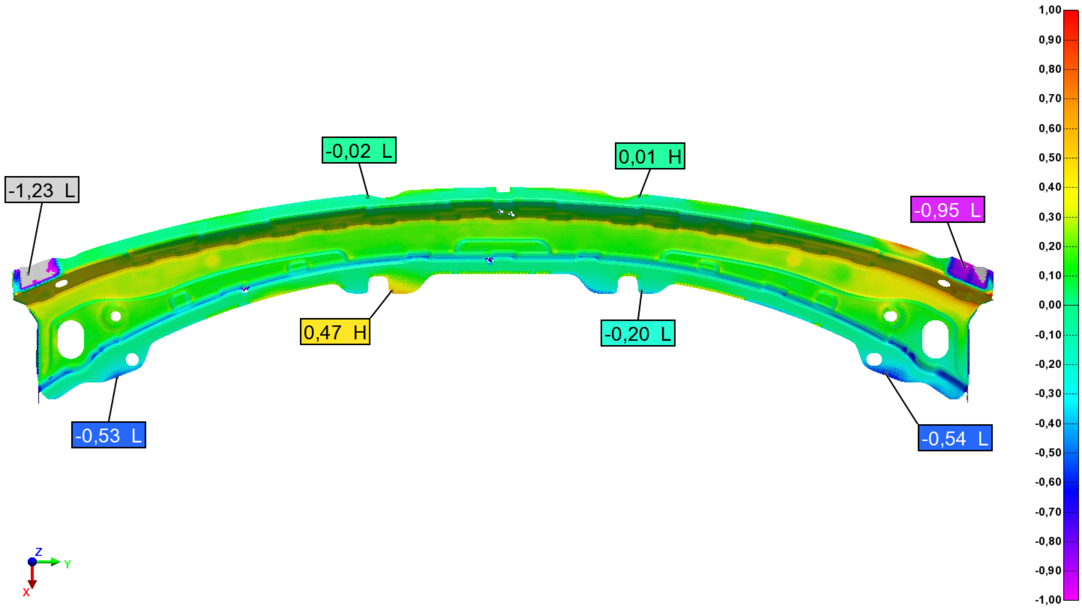


Figure 5.4: The second analysis, comparing the model from the Virtual Fixture Calculations (VFCs) with the nominal model.

When comparing the two scannings of physical fixtures with each other (see figure 5.5), the deviation will be over ±0,3mm. For two VF, the deviation is around ±0,15mm (see figure 5.6).

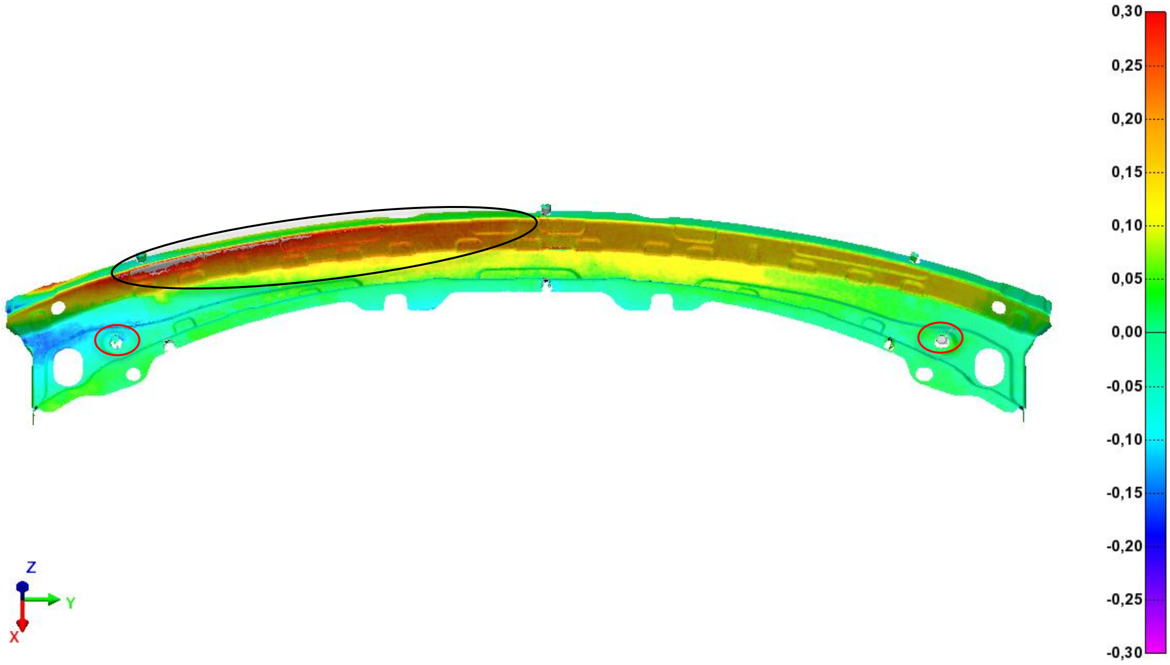


Figure 5.5: Comparing two scannings in physical fixture to each other.

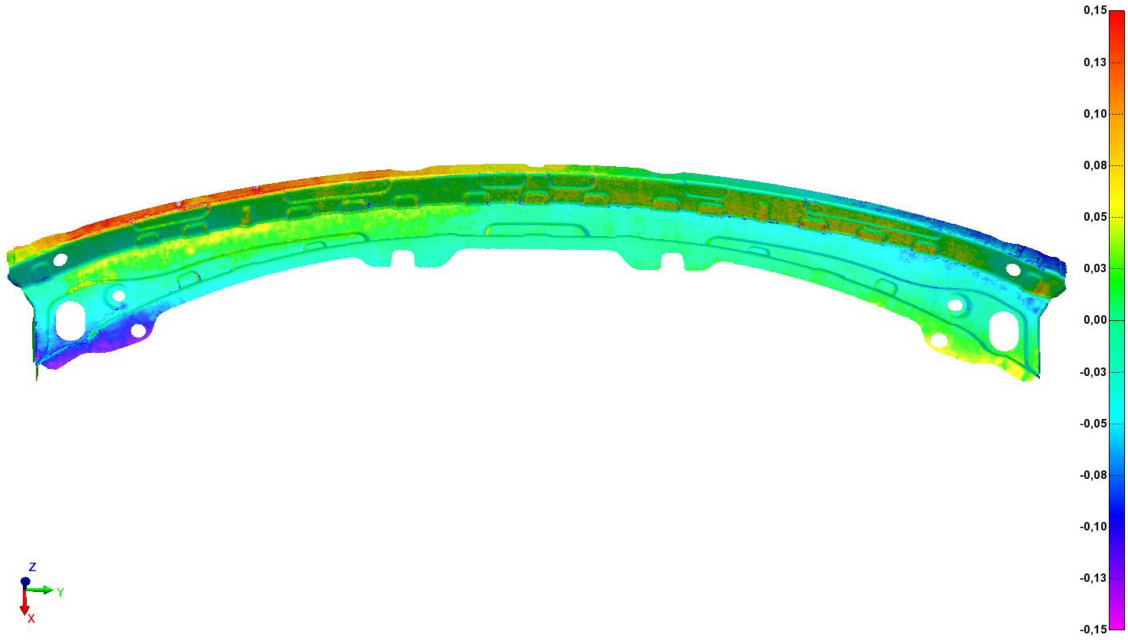


Figure 5.6: Comparing two calculated VF models to each other

The large deviations in the physical fixtures can be explained by the radiuses of holes from the pins (see red ellipse in figure 5.5) being too big and the part will not come in the same position when the parts are lifted and put down again. In the case of the sheet metal part A, the clamping sequence influence the shape measured in the fixture. The clamp pressure is so hard that it locks the part in more than one direction, which is common when using clamps, hindering the part to glide. This is why it is a large deviation on the "back wall" of the part (see black ellipse). The color plots showing deviation from nominal for the rest of the studied cases are presented in Appendix E-H

5.2 Result from interviews

The first interviewee worked as an equipment engineer. The interviewee provided information regarding material data and costs for the honeycomb fixtures. The second interviewee worked as a product manager. The interviewee provided information regarding material data and costs for the carbon fiber fixtures. In addition, the product manager provided information about costs for the containers used when transporting the physical fixtures from one country to another.

5.2.1 Results from the interviews

The different working processes of using the physical fixtures and VF are shown in figures 5.7-5.9. Figure 5.7 shows the process when using fixtures for measurements of single sheet metal parts. Figure 5.8 shows the process when using fixtures for subassemblies and figure 5.9 shows the process when the VF is used. In figure 5.7 and 5.8 there is a step called “clamping order analyze”. This means checking in which sequence to close the clamps reaching the best repeatability when reloading a part several times and change of loading operator. Depending on fixture complexity, this can take between a half to two days. This is not needed if working with the VF. When working with physical fixtures, measuring and adjusting them is necessary which can take between a half to two days to complete. This is not made when working with VF.

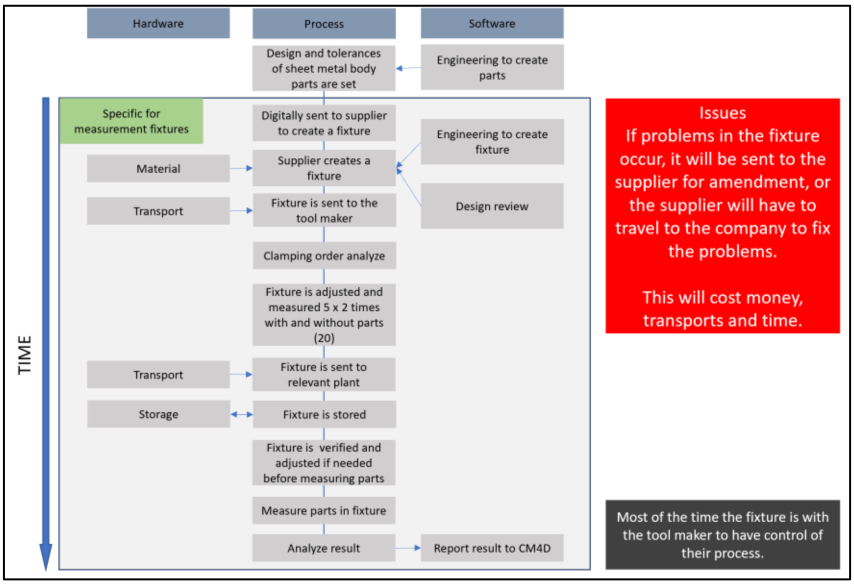


Figure 5.7: The process of using fixture for single sheet metal parts.

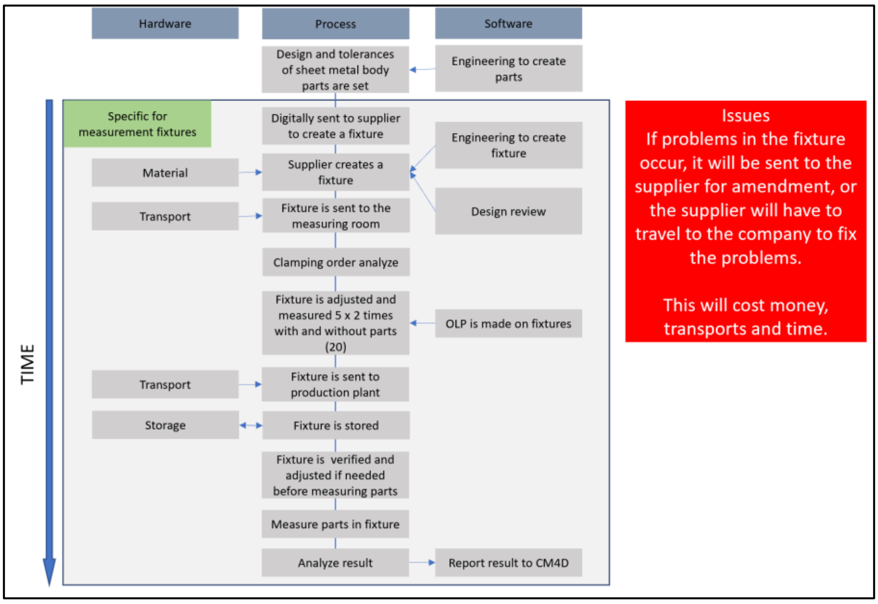


Figure 5.8: The process of using fixture for subassemblies.

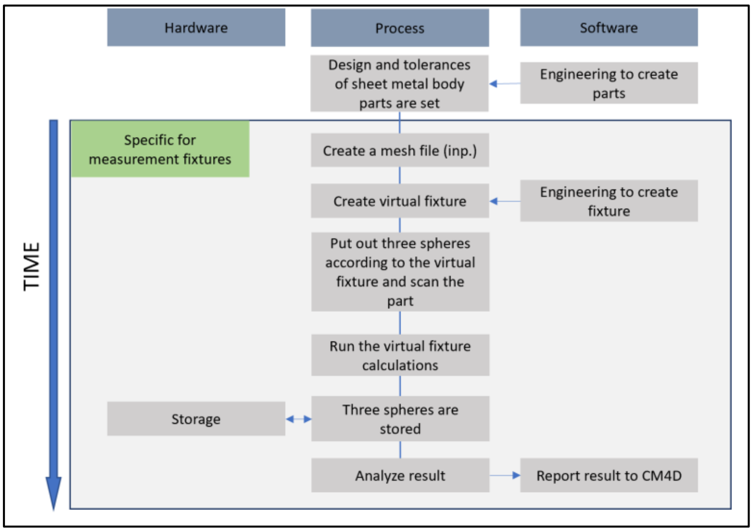


Figure 5.9: The process of using VF.

5.2.1 Savings using physical fixtures

For every car project around 75 fixtures for single sheet metal parts and around 17 fixtures for subassemblies are produced. 80-85% of the single sheet metal parts are fixtures made of aluminum and polyurethane in a honeycomb design while the subassembly fixtures are mostly carbon fiber. The honeycomb fixtures cost somewhere between 70’000-200’000 SEK, depending on size. The carbon fiber fixtures cost 80’000-380’000 SEK. The total price for the fixtures is approximately 14’000’000 SEK. The environmental effect by using and producing these will be described in chapter 5.3.

5.2.2 Transportation costs using physical fixtures

The transport of fixtures to tool maker, to the measuring room or to the plant is also a part that will be eliminated when working with the VF. In 2017, 19 fixtures were sent from Gothenburg to Charleston in USA, it was needed two 40-foot containers, and this cost about 7’000 USD which by that time was about 60’000 SEK. Since then, the price has most likely raised. The storage to keep the fixtures at the plants is also a cost that will be eliminated when using VF, apart from the spheres. Though the spheres can be moved together to barely take any extra space.

5.3 Result from LCIA

The LCIA is made on both the honeycomb fixtures and the carbon fiber fixtures. Due to the large differences in weight of the fixtures themselves, two cases are presented where one has the lowest weight and the other has the highest weight, for each fixture type.

5.3.1 Environmental impact using honeycomb fixtures

The honeycomb fixtures are created from a sandwich material made from two sheets of glass fiber reinforced with epoxy plastic with aluminum honeycomb-design (see figure 5.10).

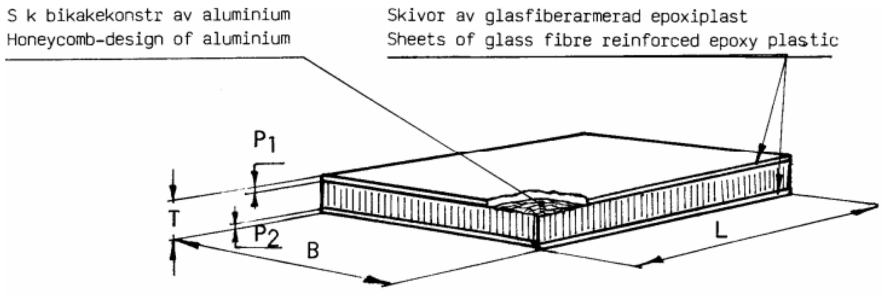


Fig 1

Tabell / Table 1

T	Leveransdimension Delivery dimensions				Vikt Weight	Artikelnr Part No.
	P1	P2	B 1)	L 1)	kg/m^2	
25	~ 0,5	~ 0,75	1220	2440	4,21	8704116
50	~ 0,5	~ 0,75	1220	2440	7,54	8704117

Figure 5.10: The material standard for physical fixtures made for single sheet metal parts

The weight of the fixtures can deviate from 15 kg to 110 kg. Due to the large difference in weight, two different scenarios are made with one being small fixtures and the other being larger fixtures. From figure 5.10, the weight for each material could be calculated for two different scenarios. Table 5.1 shows the weights. The material of the handles for the clamps is assumed to be stainless steel. One handle is assumed to weigh around 0,45 kg. For the small fixtures, it is often fewer clamps which also means fewer handles while the larger fixtures often have more handles. Three handles are calculated for the smaller fixtures while the larger fixtures use nine handles.

	Weight of epoxy	Weight of aluminum	Weight of handles
Honeycomb fixture 15 kg	10,13 kg	3,52 kg	1,35 (3)
Honeycomb fixture 110 kg	78,64 kg	27,31 kg	4,05 (9)

Table 5.1: A breakdown of weights for materials in honeycomb fixtures with numbers in brackets meaning number of handles.

The EPS is based on the phase's pre-use, use, and post-use, see table 5.2. In the pre-use and use the amount will be 100% of the material while in post-use the material is divided into different parts. In this calculation for Environmental Priority Strategies (EPS), the post-use of the materials is assumed that 60% of the material ends up in a landfill, 30% of the material can be incinerated and 10% of the materials can be reused for something else.

The total weight of each material is multiplied by the presumed percentage for each part of the phase. This value is stated in the amount. For example, in table 5.2 the amount of glass fiber epoxy is 10,13 kg. The amount in material reuse is 10% of 10,13 which is 1,013 kg. This value is later multiplied by the specific value which indicates the environmental effect. The total impact for each phase is added which gives an ELU for the whole life of a material. Then the impact for all materials is added to get the total ELU. In the case of the 15 kg honey comp fixture, the ELU is about 74. The same calculations are made for all four cases, but the EPS will be shown in the appendix. For a 110 kg honeycomb fixture, the ELU is calculated to be approximately 385 (see Appendix I).

Functional unit: A fixture

Materials & Processes		Pre-Use			Use			Post-Use																		Sum
		Production			Life			Reuse - Component			Reuse - Material			Energy recovery - combustion			Incineration - no energy recovery			Landfill			Other			
		E cost	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	Impact
	Unit	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU]
Glass fiber epoxy	kg	2,7	10,13	27,3567			0			0	-1,042	1,013	-1,05577	0,297	3,04	0,90277			0	0	6,08	0			0	27,2037448
Aluminum	kg	1,991	3,52	7,00409			0			0	-0,946	0,352	-0,33279	0	1,06	0			0	1,05E-06	2,11	2,2E-06			0	6,67129868
Stainless steel	kg	33,11	1,35	44,6985			0			0	-30,47	0,135	-4,11345	0	0,41	0			0	6,32E-07	0,81	5,1E-07			0	40,5850505
SUM				79,059			0			0			-5,502			0,9028			0			3E-06			0	74,460094

Table 5.2: An EPS for honeycomb fixtures weighing 15 kg

5.3.2 Environmental impact using carbon fiber fixtures

The size of carbon fiber fixtures can deviate as well as the honeycomb fixtures and that is why two scenarios are studied. These fixtures can weight somewhere between 20 kg to 160 kg. Table 5.3 shows the weights of the materials within the fixture.

	Weight of carbon fiber	Weight of handles
Carbon fiber fixture 20 kg	18,65 kg	1,35 kg (3)
Carbon fiber fixture 160 kg	155,95 kg	4,05 kg (9)

Table 5.3: A breakdown of weights for materials in carbon fiber fixtures with numbers in brackets meaning number of handles.

The same assumptions have been made for the carbon fiber fixtures in terms of the life phases. This results in an ELU for the 20 kg carbon fiber fixtures at approximately 489 (see Appendix J) and for the 160 kg fixtures the ELU is calculated to approximately 3869 (see Appendix K).

5.3.3 Environmental impact using three locators

The LCIA for the three locators will be negligible because of the fact that new sets of simplified supports are not required to be produced for every new car project or set of sheet metal parts.

6 Discussion
This section discusses the research questions, methodology, and results.

6.1 Discussing the first research questions
This section will discuss the first research question.

The first research question is as follows:
1. Can the Virtual Fixture make future predictions of geometrical deviation accurate enough to use in practice?

From the result in section 5 and Appendix it can be seen that the process works. The deviation between the two processes does not deviate more than ±0,3 mm. This is after putting offsets in the VF. This leads us to the question if it is right to put offsets on the VF. When comparing the result from the physical fixtures to nominal and the three-point setup to nominal we can see a clear improvement when putting in offsets to the VF. The physical fixtures will always have deviation which will result in wrong measurements when measuring physically, which is another thing that is an improvement if switching to VF.

The differences in the physical fixtures themselves and the models from the Virtual Fixture Calculations (VFC) themselves is also an argument that the process with VFC is a better choice than physical fixtures. This means the repeatability for the VFs are better.

Two of the scannings made on spheres was not possible to calculate. This was because the spheres were too close to radiuses. There is two way this can happen. The first way is shown in figure 6.1. Here the sphere is too close an inner radius. The second way is shown in figure 6.2 and happens when the sphere is too close an outer radius. The VFC cannot be completed because the surface that the sphere is resting on cannot be decided.

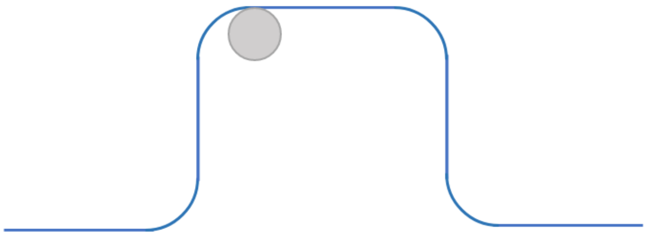


Figure 6.1: First case, where the sphere is close to the inner radius

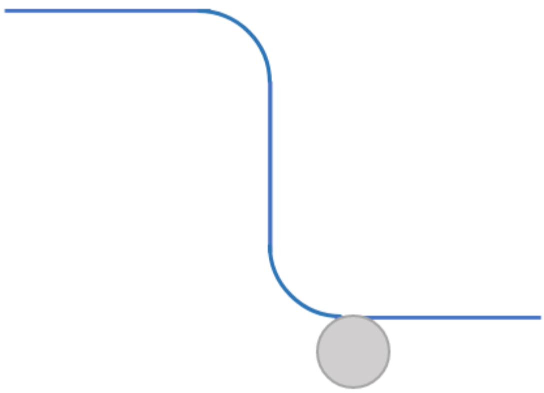


Figure 6.2: Second case, where the sphere is close to the outer radius

6.2 Discussing the second research question

This section will discuss the second research question.

The second research question is as follows:
2. Replacing the physical fixtures with the Virtual Fixtures, how will this affect the sustainability with consideration to Profit, Planet and People?

- Profit – From the results, one can see that the honeycomb fixture costs approximately 70’000-200’000SEK per fixture and the carbon fiber fixture costs approximately 80’000-380’000SEK per fixture. Therefore, by implementing the VF, the company will save up to 14MSEK per car project. Transports needed to deliver physical fixtures from for example Gothenburg to Charleston in USA, the cost will be 60’000SEK.

- Planet – From the results, one can see that the carbon fiber fixture has a higher environmental impact compared to the honeycomb fixture. By comparing the honeycomb- and carbon fiber fixture with the VF, the VF is more preferable. There is no need to transport the 3P setup fixtures around the world and these simple supports can be produced locally. Furthermore, the 3P-supports are not type bound and a limited set of supports can be used for measurement of different details.

- People – By using the VF the whole part will be measured. This will give a deeper understanding of the products and processes. With the deeper understanding it will be easier to take decisions if changes need to be done. Some people might be conservative which makes it hard to get acceptance and understanding of the benefits using a new method.

6.3 Ethical aspects of the study

The reliability of the researcher's result can be questioned if it appears to be based on unreliable data or interferes by directing the results in a certain direction. For qualitative research, there are some concerns regarding the researcher's objectivity (Kazmierska, 2020). Because the researcher designs the layout for the study, there may be concerns about objectivity because the researcher still decides who will participate in the study. For the whole study, the authors declare that the study has been conducted objectively without consciously and subjectively interfering with the results.

There are contradictions in using the Virtual Fixture by replacing the physical fixture with the VF. Implementing the VF can lead to developing new and more suitable working methods.

7 Conclusion and future work

From the results and discussions, the following conclusions are made with consideration to virtual fixtures and benefits compared with physical fixtures:

- **Small deviation differences** – When comparing the color plots made from the physical fixture and nominal with VF and nominal there is small differences. For the studied cases, the deviation was approximately 0.2 mm.

- **Repeatability** – When comparing the differences between the first and second scanning in fixtures with the different models from the Virtual Fixture Calculations (VFC) there is a smaller deviation between the VFC models. This means that there is a better repeatability using the VF.

- **Savings** – The physical fixtures from a project can cost about 14 MSEK. When changing from physical fixtures to VF this can be saved. The cost for the three spheres will have a cost initially but because the spheres can be reused to other car projects there will not be a recuring cost.

- **Lower environmental impact** – The carbon fiber fixtures have an ELU on 489-3869 and the honeycomb fixtures has an ELU on 74-385. ELU calculation has not been performed for the 3-sphere setup. We make the assumption that the ELU for these simplified reusable supports is neglible compared with today's measurement fixtures.

- **Transport** – When changing to VF, the transports for the physical fixtures around the world will not be needed. The three spheres can be manufactured locally which will not require any longer transportations.

The future work that is recommended is:

- **Wider study** – Studying more sheet metal parts with various form, size and stiffness. This is to study the behavior of a wider collection of parts included in a car body.

- **Deeper study** – Studying the same sheet metal parts more times (25 times) with various form, size and stiffness. This is made to furthermore verify the repeatability.

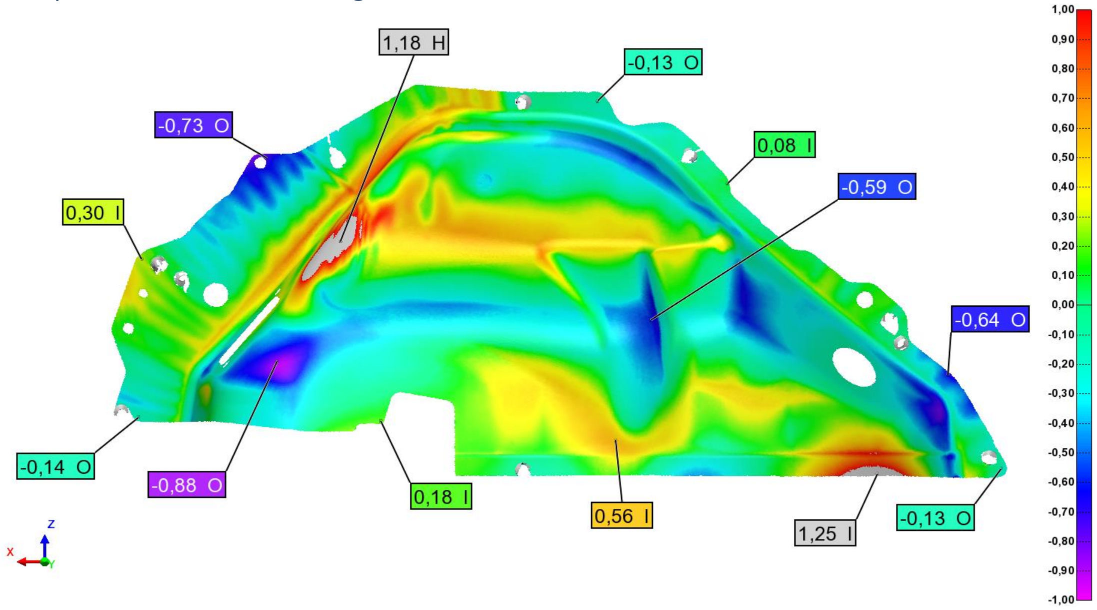
- **Education** – Manuals and presentations in video format can be used to educate employees to use the VF-method.

- **Acceptance** – Selling the concept and getting acceptance is the last recommendation. Doing this makes employees aware of this new technology.

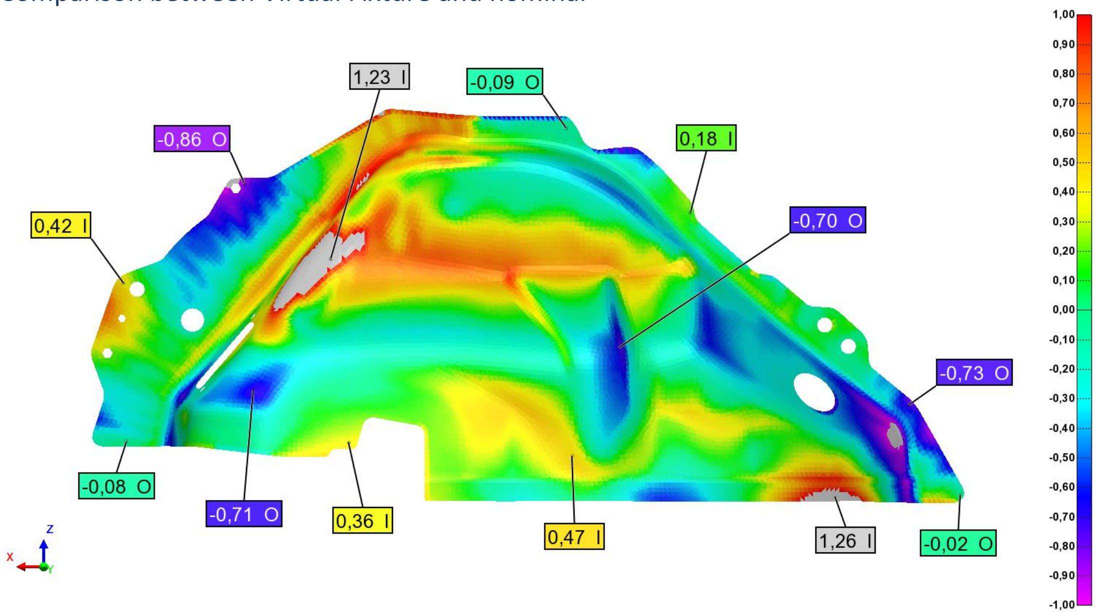
8 Appendix

A: WHEELHOUSE REAR INNER LH comparison

Comparison between scanning in fixture and nominal

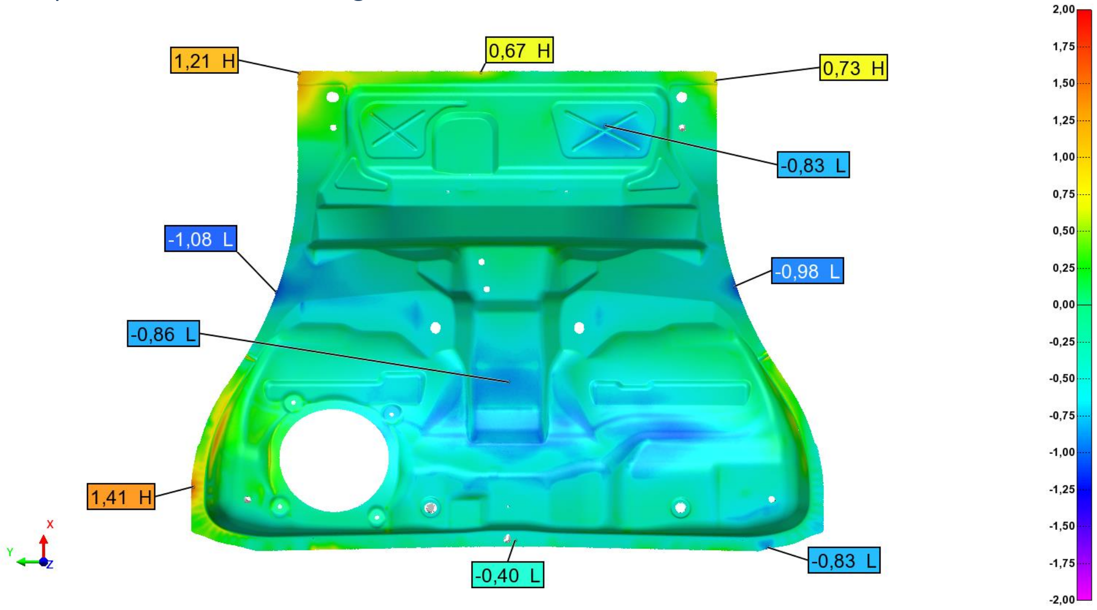


Comparison between Virtual Fixture and nominal

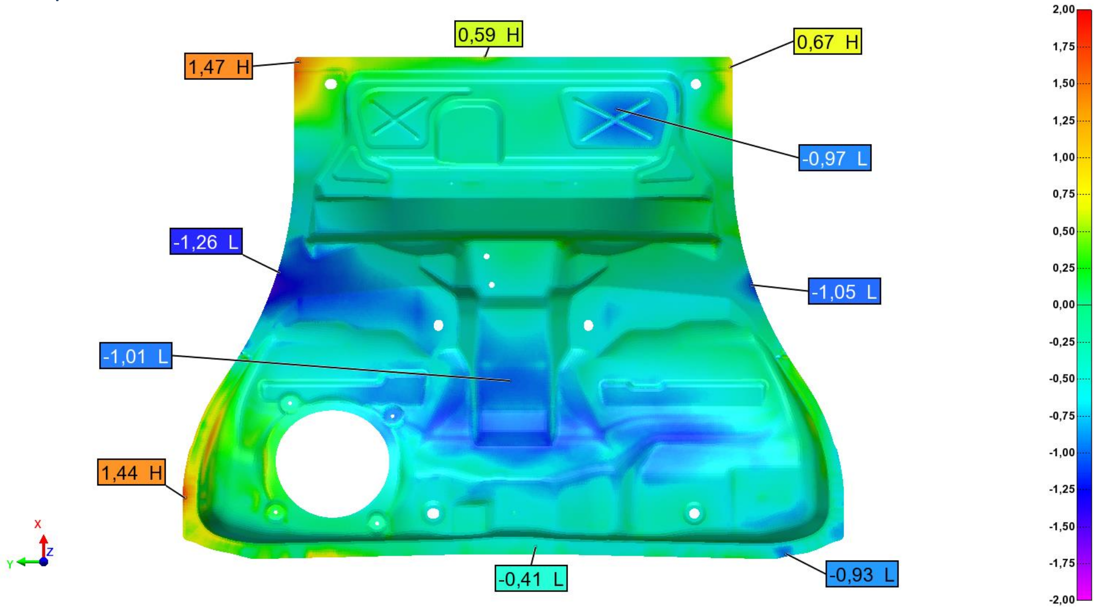


B: REAR FLOOR PANEL FRONT comparison

Comparison between scanning in fixture and nominal

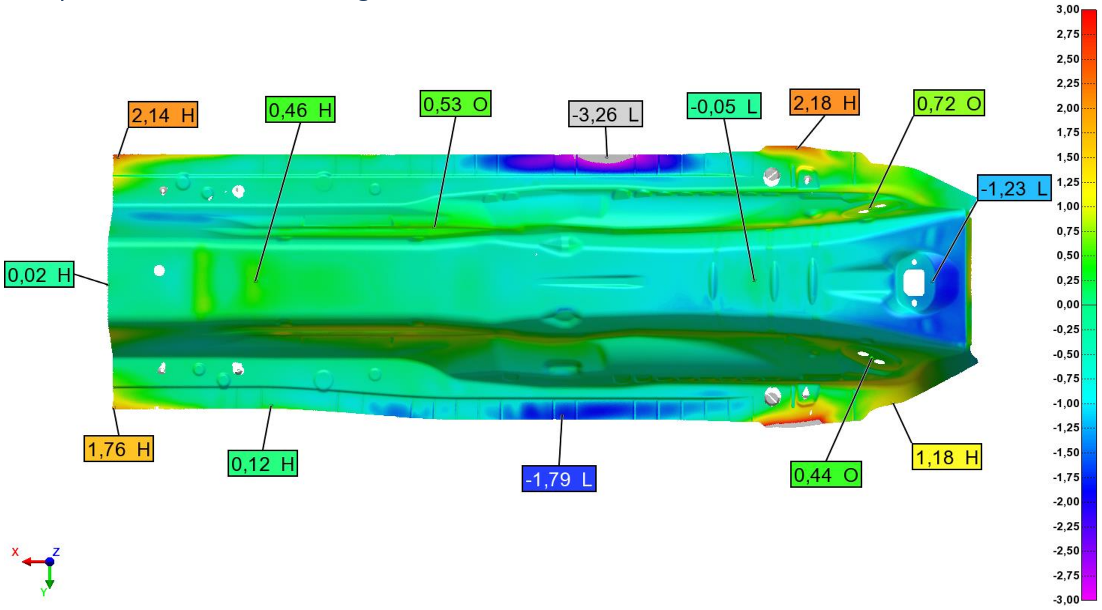


Comparison between Virtual Fixture and nominal

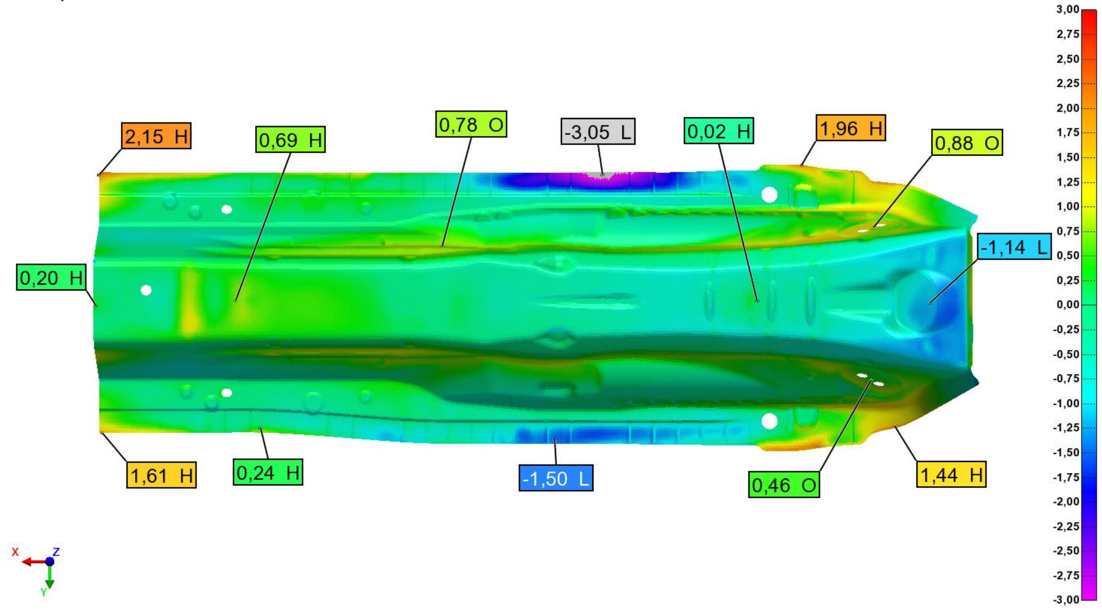


C: Tunnel comparison

Comparison between scanning in fixture and nominal

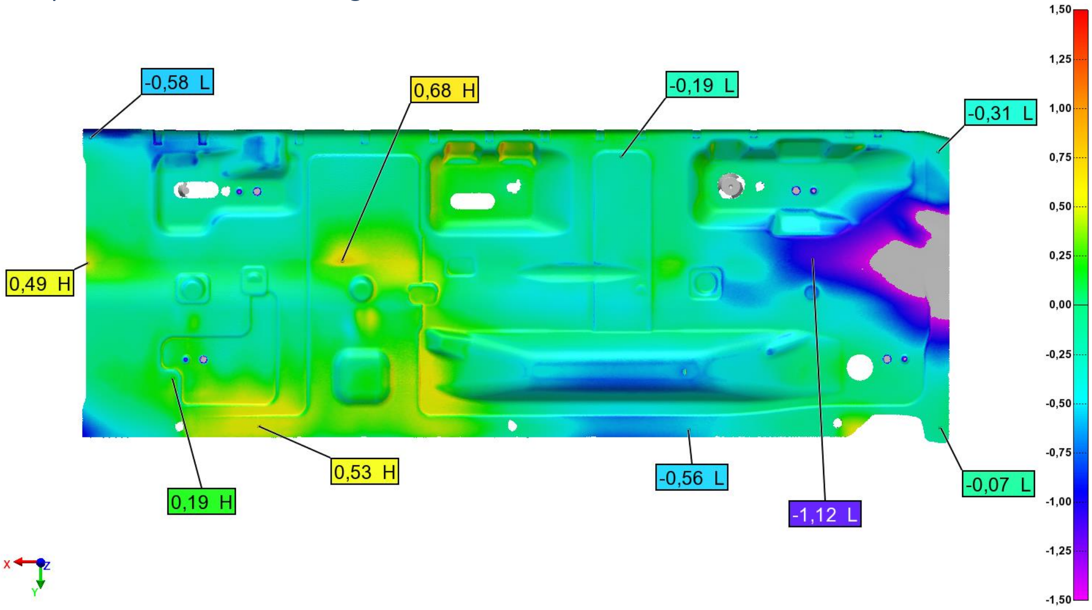


Comparison between Virtual Fixture and nominal

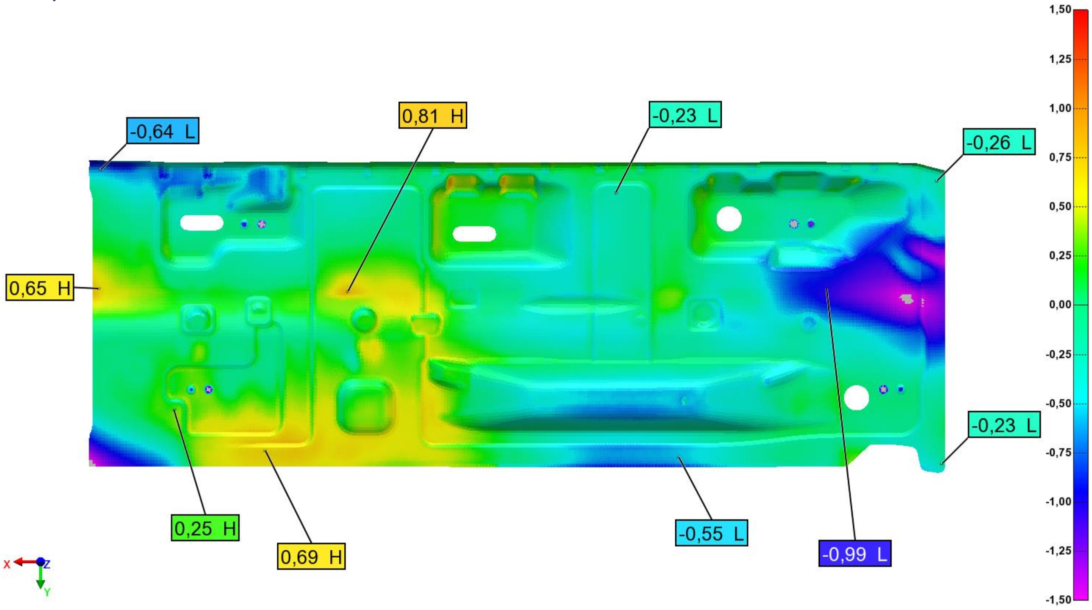


D: PANEL FRONT FLOOR LH comparison

Comparison between scanning in fixture and nominal

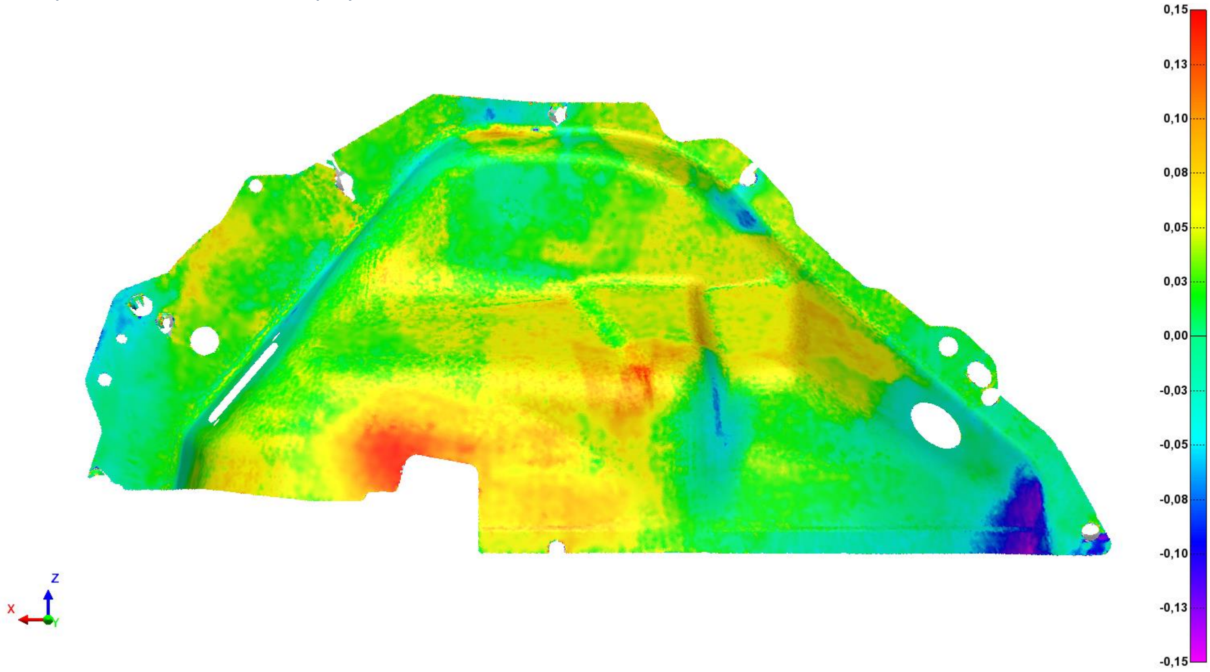


Comparison between Virtual Fixture and nominal

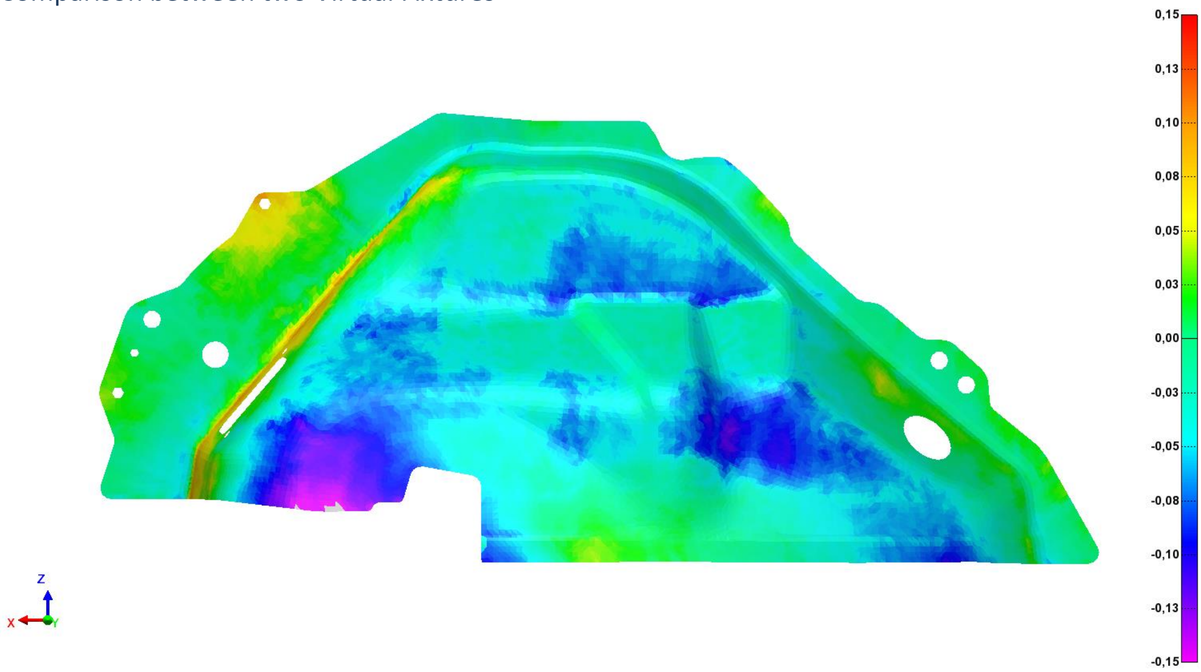


E: WHEELHOUSE REAR INNER LH repeatability study

Comparison between two physical fixtures

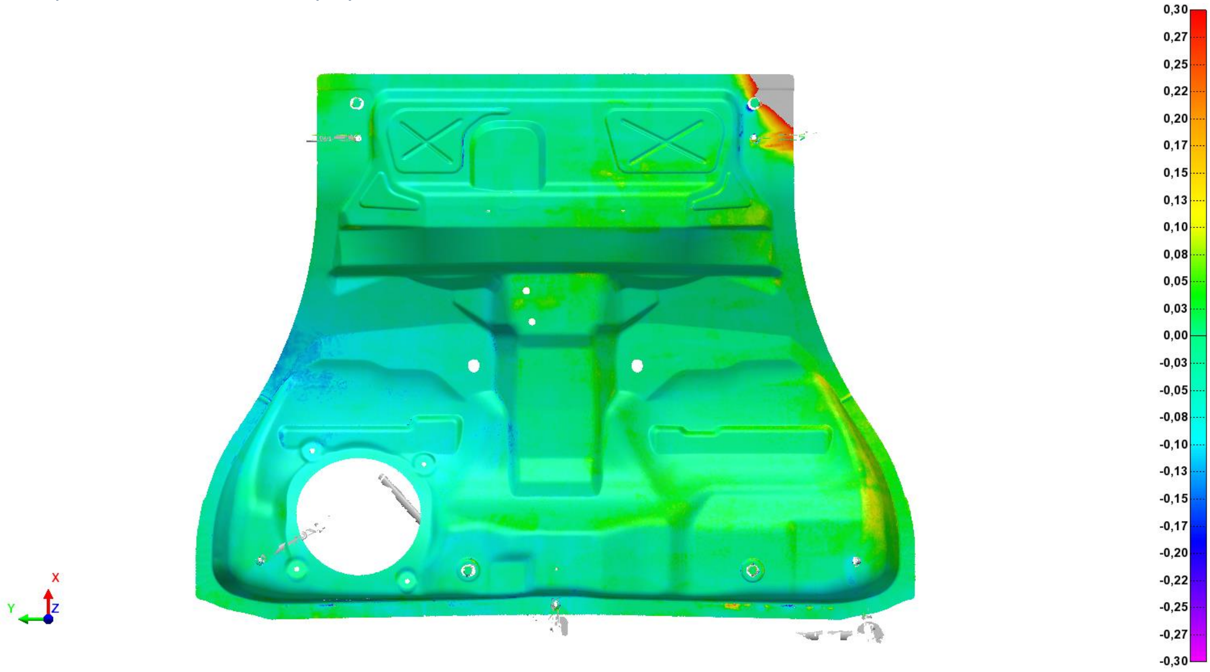


Comparison between two Virtual Fixtures

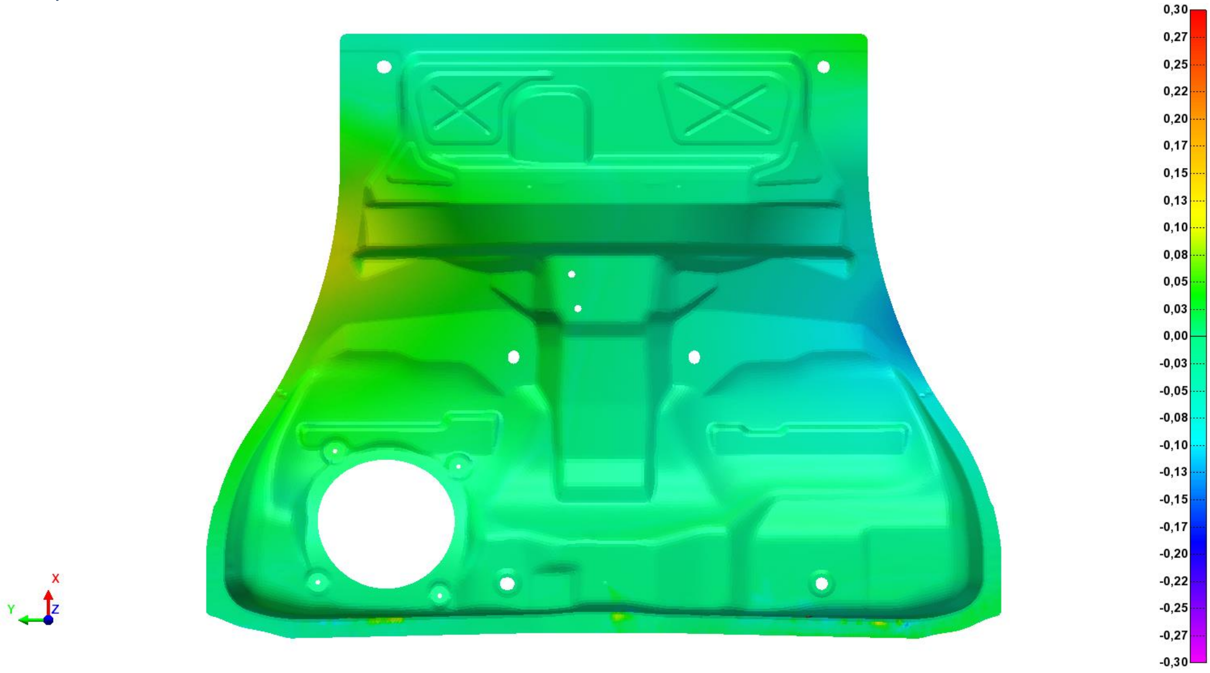


F: REAR FLOOR PANEL FRONT repeatability study

Comparison between two physical fixtures

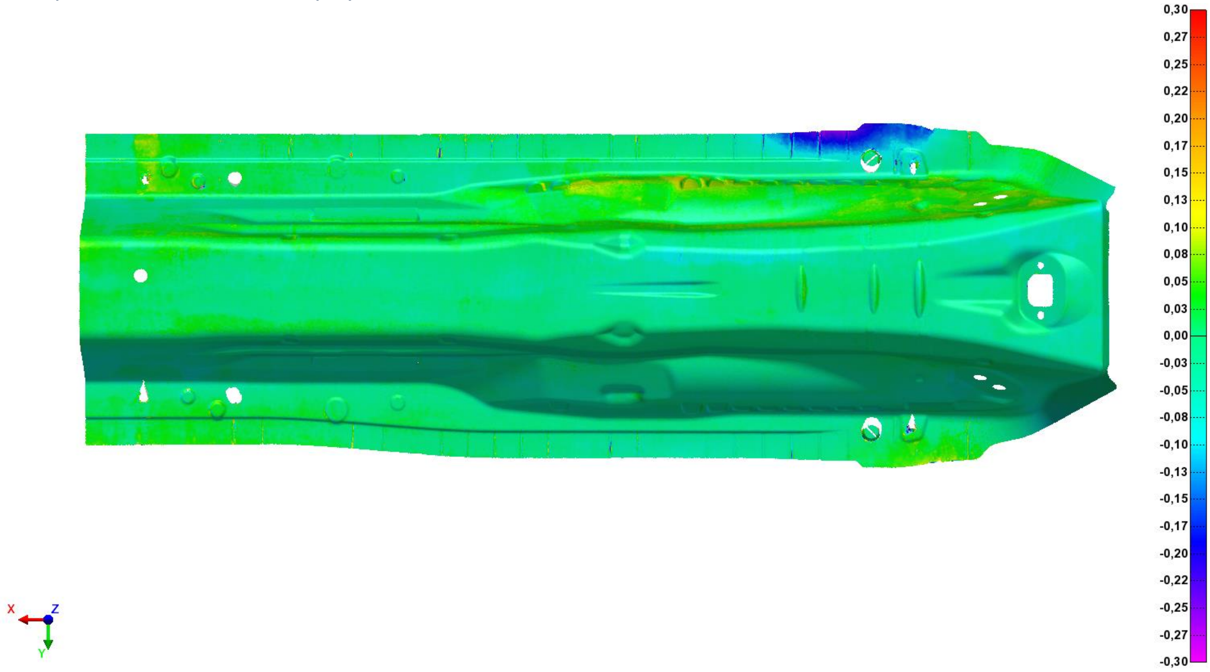


Comparison between two Virtual Fixtures

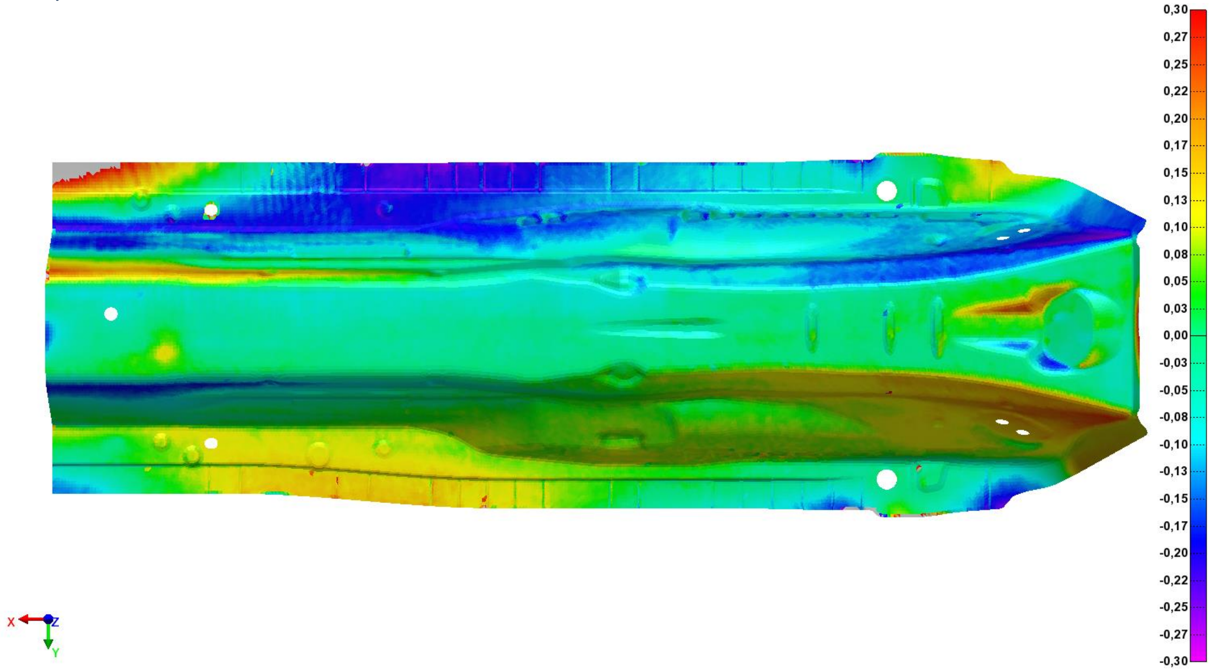


G: Tunnel repeatability study

Comparison between two physical fixtures

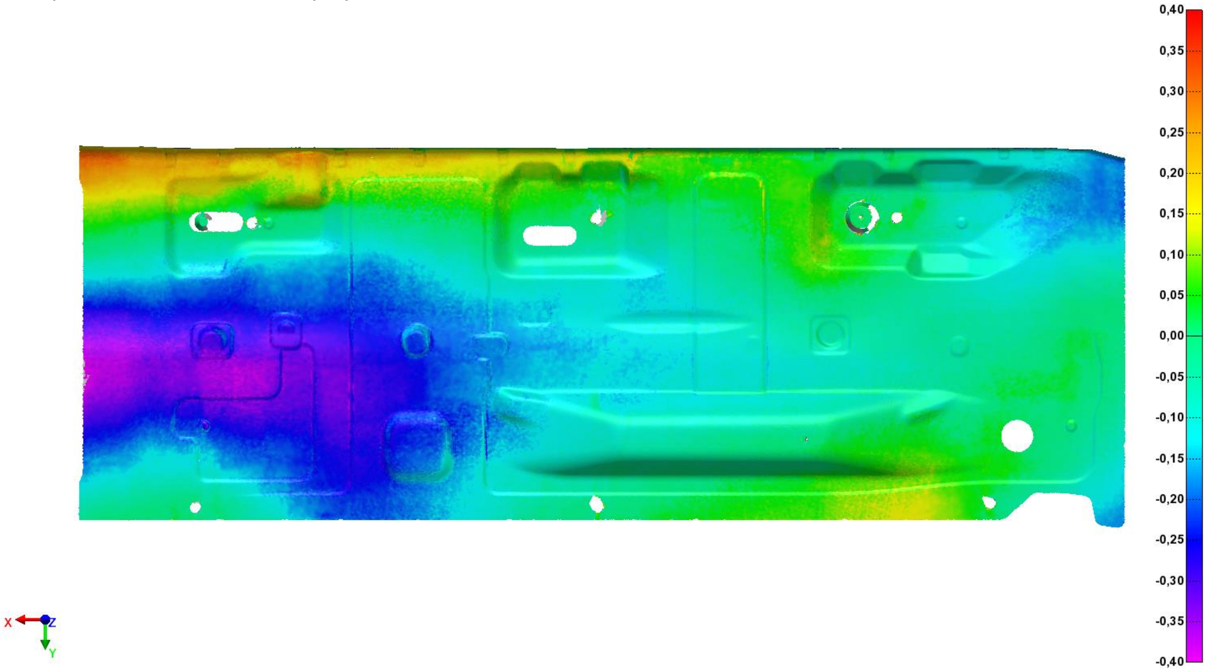


Comparison between two Virtual Fixtures

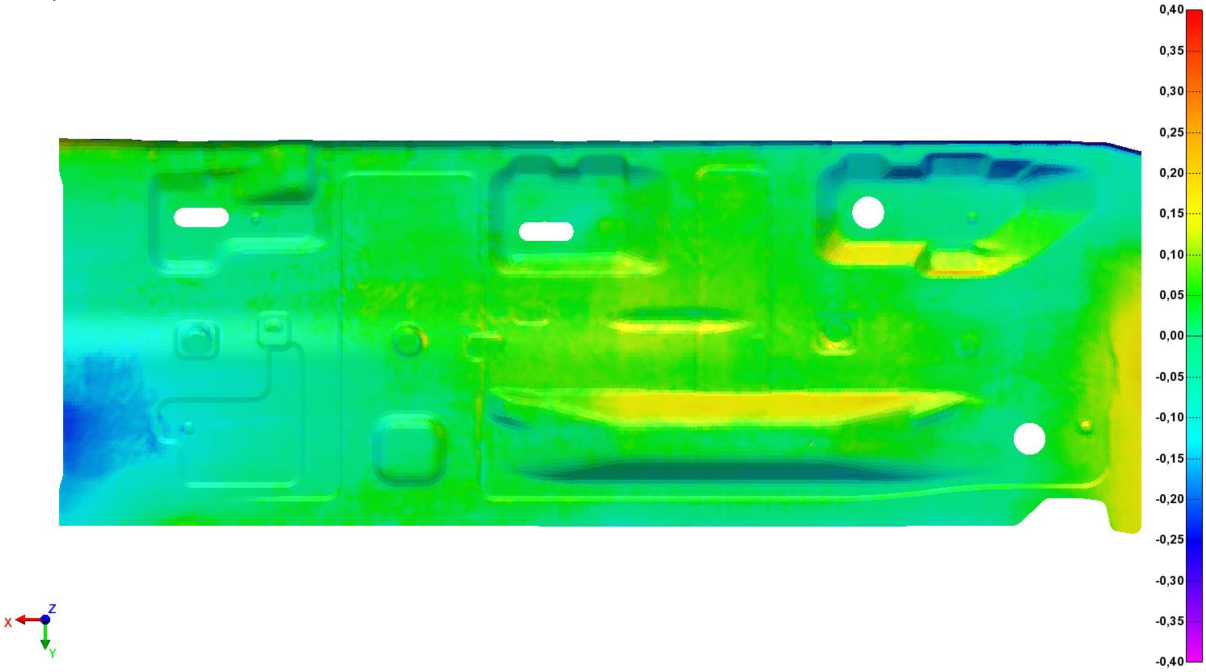


H: PANEL FRONT FLOOR LH repeatability study

Comparison between two physical fixtures



Comparison between two Virtual Fixtures



I: Environmental Priority Strategies for honeycomb fixtures weighting 110 kg

Functional unit: A fixture

Processes		Pre-Use			Use			Post-Use																		Sum
		Production			Life			Reuse - Component			Reuse - Material			Energy recovery - combustion			Incineration - no energy recovery			Landfill			Other			
		E cost	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	index	Amount	Impact	Impact
	Unit	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU/ unit]		[ELU]	[ELU]
Glass fiber epoxy	kg	2.7	78.64	212.34			0			0	-1.042	7.8645	-8.195	0.297	23.593	7.0072			0	0	47.187	0			0	211.15288
Aluminum	kg	1.991	27.31	54.365			0			0	-0.946	2.7305	-2.583	0	8.1916	0			0	1.05E-06	16.383	2E-05			0	51.781985
Stainless steel	kg	33.11	4.05	134.1			0			0	-30.47	0.405	-12.34	0	1.215	0			0	6.32E-07	2.43	2E-06			0	121.75515
SUM				400.8			0			0			-23.12			7.0072			0			2E-05			0	384.69001

J: Environmental Priority Strategies for carbon fiber fixtures weighting 20 kg

Functional unit: A fixture																										
Processes		Pre-Use			Use			Post-Use																		Sum
		Production			Life			Reuse - Component			Reuse - Material			Energy recovery - combustion			Incineration - no energy recovery			Landfill			Other			
	Unit	E cost [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	index [ELU/unit]	Amount	Impact [ELU]	Impact [ELU]
Carbon fiber	kg	25	18.65	466.25			0			0	-12.57	1.865	-23.44	0.9462	5.595	5.294			0	0	11.19	0			0	448.10094
Stainless steel	kg	33.11	1.35	44.699			0			0	-30.47	0.135	-4.113	0	0.405	0			0	6.32E-07	0.81	5E-07			0	40.585051
SUM				510.95			0			0			-27.56			5.294			0			5E-07			0	488.68599

K: Environmental Priority Strategies for carbon fiber fixtures weighting 160 kg

Functional unit: A fixture

Processes		Pre-Use			Use			Post-Use																		Sum
		Production			Life			Reuse - Component			Reuse - Material			Energy recovery - combustion			Incineration - no energy recovery			Landfill			Other			
	Unit	E cost [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	index [ELU/ unit]	Amount	Impact [ELU]	Impact [ELU]
Carbon fiber	kg	25	155.95	3898.8			0			0	-12.57	15.595	-196	0.9462	46.785	44.268			0	0	93.57	0			0	3746.9888
Stainless steel	kg	33.11	4.05	134.1			0			0	-30.47	0.405	-12.34	0	1.215	0			0	6.32E-07	2.43	2E-06			0	121.75515
SUM				4032.8			0			0			-208.4			44.268			0			2E-06			0	3868.744

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