

## Treball final de grau

**Estudi: Doble titulació GETI - ADE**

**Títol:** ESTUDI DIMENSIONAL DEL DESGAST I VIDA DE MOTLLES IMPRESOS EN 3D UTILITZATS PER A DEFORMAR XAPES MITJANÇANT TERMOCONFORMACIO. PROTOCOLS D'US I METODOLOGIA PEL TRACTAMENT DE DADES.

**Title:** DIMENSIONAL STUDY OF THE WEAR AND LIFE OF 3D PRINTED MOLDS USED TO DEFORM SHEETS THROUGH THERMOFORMING. USE PROTOCOLS AND DATA PROCESSING METHODOLOGY.

**Document:** 1. Memòria i Annexos

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## Memory



## 1. Introduction

### 1.1. Object of this project

The present project does have as a main objective to explore the capabilities or limitations of a coordinate machine (CMM) and a 3D scanner, as well as the usage of different software, through the analysis of the wear of 3D printed die of a thermoforming operation, in order to establish usage protocols, methodology recommendations, etc. for the processing of the data taken and, thus, be able to make a comparison between the results obtained.

Therefore, the results obtained, should allow to study:

- i) The wear of the molds,
- ii) The dimensional accuracy of the thermoformed sheets with regards to its comparison with the printed mold.

The focus of the analysis of the molds and sheets will be based on obtaining the profiles and the images extracted from the machines for dimensional analysis that the Gr3p research group has in its laboratory (coordinate machine, 3D scanner).

### 1.2. Scope & specifications

Given that there are many variables to take into account, the following tasks have been performed during the process:

- Study and understanding of the thermoforming conformation process.
- Study of the material characteristics of 3D printed PLA, as well as PC and PVC.
- Printing of the 3D PLA die.
- Study of the deformed material data and mold data.
- Mold deformation and wear after stress and usage under high temperatures during the thermoforming process.
- Dimensional difference and accuracy between the three stages of the mold:
  - o 1. The mold design
  - o 2. The mold 3D printed
  - o 3. The mold after thermoforming
- Thermoformed sheets dimensions and profiles accuracy with regards to the mold, both PC and PVC.
- Study of shear deformation of PC & PVC sheets as well as 3D printed PLA material.

- Usage of a 3D scan and coordinate machine in order to take an accurate data of the PC & PVC thermoformed sheets profiles and height difference between sheets and mold.
- Data transfer protocol from coordinate machine (CMM) values to profile. Via software.
- Data transfer protocol of the 3D mold after thermoforming to software. Via scan.
- Comparison methods of the mold different stages. 3D software visual model differences and data similarity, via SolidWorks and Geomagic.
- Data transfer protocol of the PC & PVC deformed sheets to software. Via scan.
- Comparison methods of the PC & PVC deformed sheets, regarding their temperature exposure. Via SolidWorks and Geomagic.
- Comparison methods of PC & PVC deformed sheets regarding its dimensional accuracy with the 3D mold. Via SolidWorks and Geomagic.
- Comparison method of PC & PVC different analysis. Superposition of CMM and 3Dscan results.
- Time management and time efficiency for the data protocol process.

### 1.3. Project Requirements

The following table, *Table 1*, exemplifies the different requirements set up for this project as well as a small detail about it, while giving a hint of its accomplishment.

*Table 1. Project requirements*

Project requirements	Detail
AIM	Study the dimensional accuracy process of thermoforming, via 3D scanning and CMM hardware, and different software.
METHODOLOGY	Performance of the thermoforming process
	Usage of CMM to take data.
	Usage of a 3D scan to take data.
	Usage of a specific methodology path to treat CMM data.
EQUIPMENT	Usage of a specific methodology path to treat 3D scanned data.
	Mitutoyo model Crysta-Apex C544 coordinate measuring machine (CMM)
	3D scanner EinScan Pro 2X.
	Mitutoyo Surftest SV2000.
	PC & PVC sheets.
	Formech 450, Thermoforming Equipment
	Microsoft Office
	Solid Works
	Geomagic Essentials
	Shining 3D
	PLA 3D printed die
BCN Cura Sigma R19 3D printer	
MATERIALS	PC sheets
	PVC sheets
	PLA filament
EXPERIMENTATION	Propose a valid CMM methodology analysis for the thermoformed die, PC and PVC data.
	Propose a valid 3D Scanning methodology analysis for the thermoformed die, PC and PVC data.
TIMING	Due to 06/2023.
ANALYSIS RESULTS	Evaluate and quantify the die wear during the thermoforming process.
	Evaluate and quantify the PC and PVC wear during the thermoforming process.
	Obtain of an optimized methodology for treating CMM and/or 3D scanned data.
COSTS	Correct budgeting of the whole process by evaluating, optimizing and minimizing overall project costs.

## 2. Antecedents / SoA

Non-conventional manufacturing technologies, such as additive manufacturing, have a growing presence in the actual industry, mainly in prototyping, development of customised products and also in the manufacture of tooling and molds for other manufacturing processes.

The Gr3p research group has experience in the deformation of polymeric sheets by incremental deformation, and has also used 3D printers to create molds to deform and study polycarbonate (PC) and polyvinyl chloride (PVC) plastic sheets, two biocompatible polymers.

As a precedent for the work, the former student Paulwin Joby Kundukulam, carried out a Master's Thesis in a stage at Gr3p research group. It compares the results from Incremental Sheet forming process, from previous studies made at Gr3p with Thermoforming process, in terms of formability and geometrical analysis.

For the actual thesis, the following points from the Master's Thesis work are being used and have a relative importance:

- A 3D printed mold had been designed and created,
- PC & PVC sheets had been deformed through thermoforming manufacturing process,

On top of that, the initial work of the current thesis did converge in time and place with the Master's Thesis previously mentioned, therefore the knowledge of the current thesis's background and implication in it is a huge factor to understand, treat, analyse the data and create its protocols for a better study.

Moreover, a precedent work made by the former University of Girona student Joan Coma, carried out a Degree Thesis at Gr3p research group where he did study the usage of PC and PVC sheets for deformation and 3D printer usage for another deformation process. In this case, it was Incremental Sheet Forming (ISF). Following, it can be found a diagram about the previous data in *Chart 1* and background of the current project in *Chart 2*.

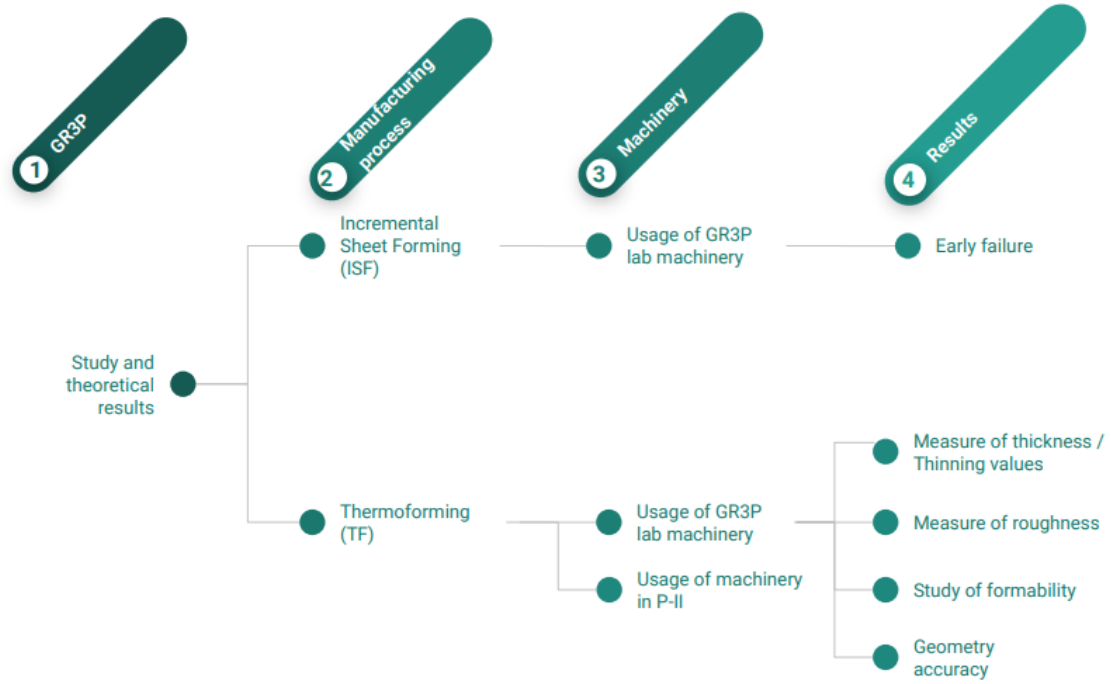


Chart 1. Background of precedent thesis; Source: Author's own elaboration

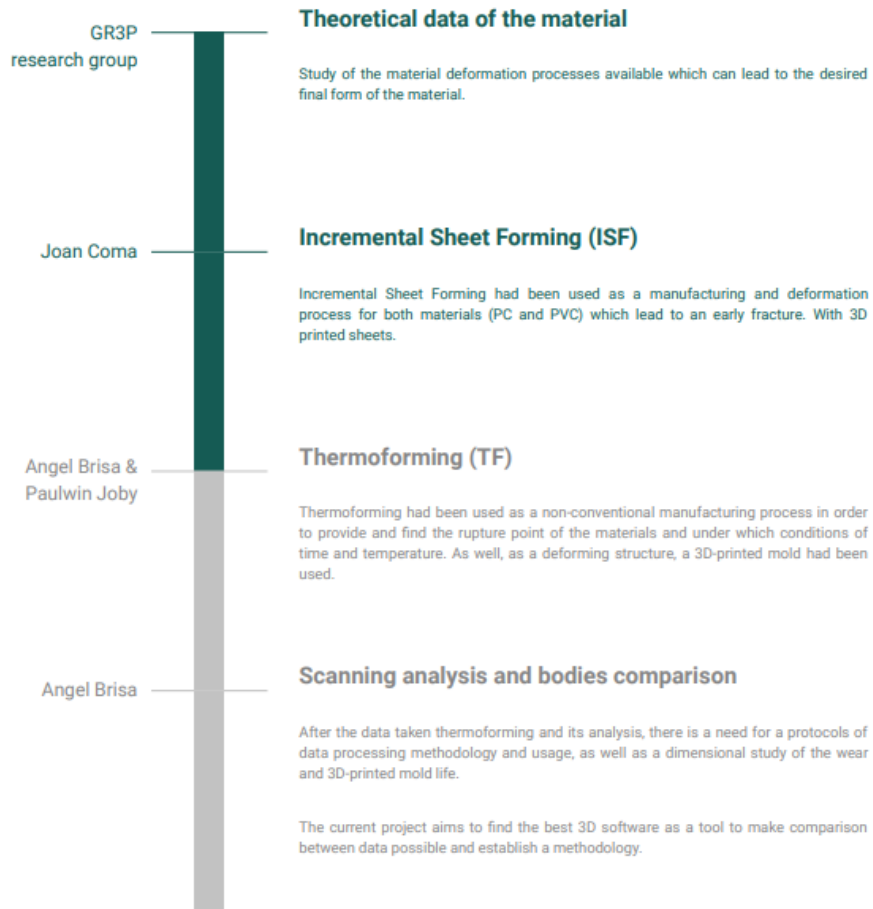


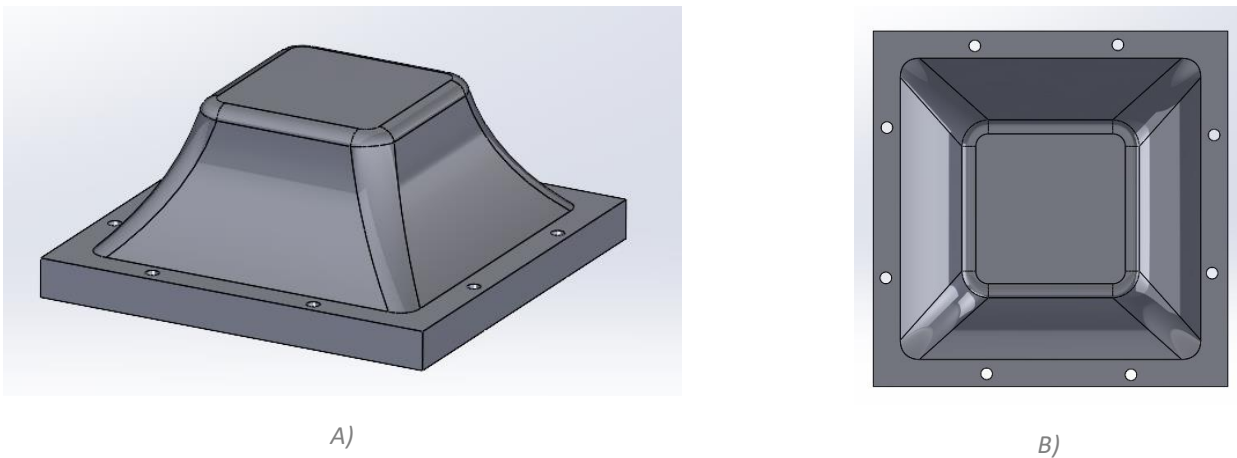
Chart 2. Precedent thesis and current moment of the study; Source: Author's own elaboration

## 2.1. Starting point

The project does start with the thermoforming process data performed in the lab. Following, there is a brief explanation of methodology used in the *Thermoforming proces*, as well as the definition of the terminology used for the main elements which are treated. The thermoforming operation main elements are listed below:

- A Formech 450 thermoforming machine and equipment,
- 3D printed mold, denominated "DIE 3".
- A thermoplastic sheet. PC and PVC sheets were used as thermoplastic sheet materials.

For the DIE 3 design, *Illustration 1*, the previous work from Paulwin has been used.



*Illustration 1. A) General overview; B) Topside view*

Even though in the next paragraph there is the mainly process explained, detailed information about the thermoforming process performed, the thermoforming machine, as well as the 3D mold additive printing process, and materials key properties are explained in *Annex I .- Thermoforming. General definition, Annex II.- Thermoforming machine used, Annex III.- 3D printed mold (DIE3)* and in



*Annex IV.*- Thermoplastic sheets as well.

In *Illustration 2*, a thermal camera can be seen. It is a FLIR Thermal Camera 480, which was used to capture the sheets temperature all along their surface just after deformation occurred.

Following each step of forming we now obtain the perfectly molded sheet. The same procedure is repeated for both the materials and the final mold can be obtained which is like the results from the incremental sheet forming which has been done before. Further the molds obtained from thermoforming by using the 3D printed mold is now analyzed considering various aspects.

Plastic sheets to be molded should have a greater length and width than the finished product. They are clamped into a holding device and heated in order to raise it to the forming temperature. The sheet is heated by contact heating using panels as heat conduction. This heating process is mandatory for the forming process since it creates the necessary pliability and flexibility.

Heated plastic sheets are removed from the heating equipment and transported to a temperature-controlled and pre-heated mold tool. At this stage, the plastic sheet takes the shape of the mold cavity, which contains the desired form of the finished product. This stage gives the product its three-dimensional characteristics.

In the current case of study, a positive tool or male mold has been used, the DIE3, which convex-shapes the plain heated sheet, which gives the final shape to the plastic sheet.

After forming, the thermoformed plastic solidifies its new shape by cooling using air in vacuum, *Illustration 2*. The tool material used significantly affects the cooling cycle, thus also affecting the quality of the parts.



Process diagram 1. Thermoforming process

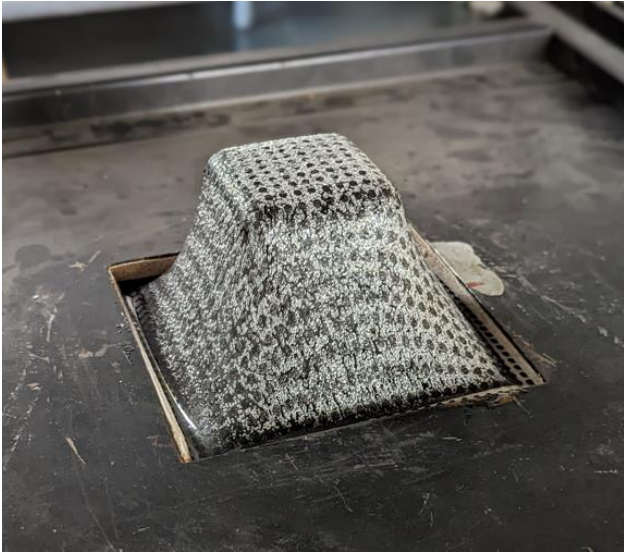


A)

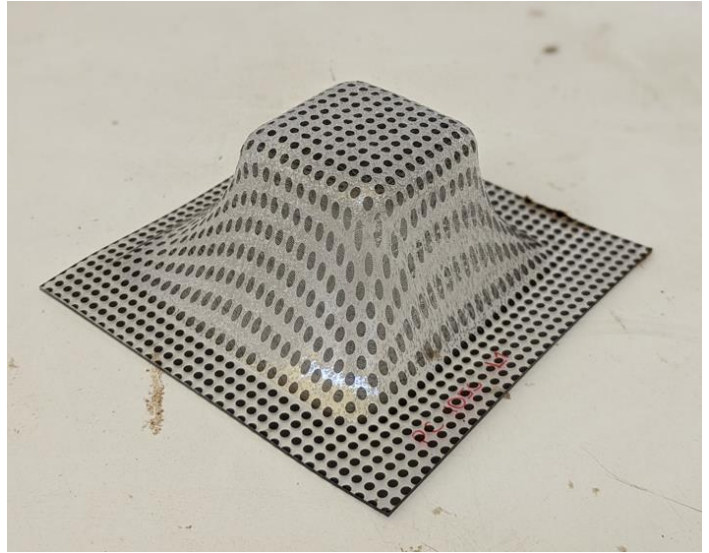


B)

Illustration 2. A) Position 1. Sheet clamped, heater reaching desired temperature; B) Position 2. PC/PVC sheet being heated



A)



B)

*Illustration 3. A) Thermoplastic being deformed; B) Final shape*

### 3. Methodology and used equipment

#### 3.1. CMM Profiles data obtain

This section aim is to describe the targeted data to be obtained through the use of the CMM machine equipment, and which bodies and thermoplastics will be used as data taking specimen.

##### 3.1.1. Experimental work plan

With the aim of ensuring the repeatability of the analysis in order to ensure its future capabilities with different bodies, it is looked to obtain the profile for each body.

The CMM will give the coordinates of the shape's body, with an accuracy of  $\pm 0.001\text{mm}$ , allowing a high dimensional accuracy.

Regarding the mold, the following profiles will be explored, treated and analysed:

**Note.** It will be referred to the 3D-printed PLA mold as DIE3.

- DIE 3 – Design -> Data taken out from the CAD version of the DIE3. Mold design.
- DIE 3 – Before -> Data taken out from the mold state after being 3D-printed.
- DIE 3 – After -> Data taken out from the mold state after thermoforming sheets.

Since DIE 3's topside is a bi-dimensional planar surface, it can be studied for determining the wear caused during the thermoforming process. Therefore, extra profiles of the DIE 3 – After will be taken.

Regarding the thermoformed sheets, following it is shown their nomenclature meaning *Table 2*, and which of them will be explored:

- Material: It has been worked with either polycarbonate (PC) or polyvinyl chloride (PVC), which characteristics are detailed in

- *Annex IV.- Thermoplastic sheets.*
- **Time:** It shows the amount of time at which the sheet has been under temperature, being thermoformed. (90, 105 or 120 seconds)
- **#Sheet:** It shows the number of sheets which has been used in this exact material and under this amount of time. (#1, #2 or #3)

*Table 2.- Label name for each PC & PVC specimen analyzed*

PVC	PVC_90_S1	PVC_90_S2	PVC_90_S3	PVC_105_S1	PVC_105_S2	PVC_105_S3	PVC_120_S1	PVC_120_S2	PVC_120_S3
PC	PC_90_S1	PC_90_S2	PC_90_S3	PC_105_S1	PC_105_S2	PC_105_S3	PC_120_S1	PC_120_S2	PC_120_S3

### 3.1.2. Data analysis

The equipment used to take the data analysis, is a Mitutoyo model Crysta-Apex C544 coordinate measuring Machine (CMM), *Illustration 4*, using Mitutoyo SurfTest SV2000 as software.

The machine allows taking the position (X, Y, Z) out of shapes and, in this projects case, it will be used to take coordinates data from PVC and PC thermoformed sheets, creating a section profile of the different heights, which will be used later on for comparison.

The data taken from each PC, PVC sheet and mold, will be a whole profile section and the profile data will be taken in steps of 0.8mm between them.

For extra context, **Error! No s'ha trobat l'origen de la referència.** shows the coordinate machine taking data.

There are many different reasons on why to study and compare this data. The main aims are mentioned below:

- Study the dimensional accuracy of the 3D printing process of the mold.
- Study the PLA material wear for the thermoforming process.
- Dimensional study of the PVC and PC sheets after thermoforming.
- Height differences between mold and PVC & PC sheets dimensions.



*Illustration 4.- Mitutoyo Crysta-Apex C544 CMM*

### 3.1.3. Expected results analyses

The expected results analyses are the following:

#### ***DIE analysis: 3D printing process accuracy***

There is a tolerance of the manufacturing process for 3D printing the mold, which should be study and taken into account before studying the DIE3 – After, since DIE3 – Before is actually the starting point of the DIE3 before usage and, therefore, before thermal wear takes place.

In order to study correctly the dimensional accuracy of the mold 3D printing process, it will be used both the CMM machine, as well as the software used for designing the mold, Solidworks, in order to take the data out.

Because of the difference of procedure in data extraction, the data will be converged in Excel so that it can be equally treated and comparisons can be rightly performed.

Since the 3D printer parameters have been highly studied and DIE3 mold is an iterative mold carefully designed, a high accuracy is expected to take place. Therefore, the following statement is expected:

$$DIE3 \text{ Solidworks} \approx DIE3 \text{ Before}$$

One profile will be taken from the DIE3 – Before with the CMM machine, which will then be compared with a DIE3 – Solidworks profile, given the expected uniformity of the 3D printing process.

#### ***DIE analysis: Thermoforming process wear***

Given the thermal stress under which the DIE3 works during the thermoforming process, it should be able to determine a methodology for the data treatment of the DIE3 – After, regarding the easy of taking data every each precise coordinates in the CMM machine.

Even though a dimensional difference is expected to take place, it is uncertain yet if the mold will shrunk or dilate due to the thermal forces. What is known, though, is that the mold topside is the part which will be more affected. Therefore, not only one profile will be taken from DIE 3 – After but also a topside data pattern will be created, in order to have an accurate superficial map of the DIE3 after thermoforming takes place.

$$DIE3 - \text{Before} = DIE3 - \text{After} ?$$

Also, a datasheet comparison has been created with the 3 different DIE3 states.

The reason of unknowing which body will have a higher dimension, is due to both following processes taking place:

- The displacement of layers during the thermoforming process due to thermal stress, which could lead to diminish the height at some points while increase in other zones, or even a “crushing” effect on the body.
- The shrinking process which takes place during the cooling of the body after being thermoformed.

### ***PVC & PC sheets data analysis***

PVC & PC “datasheets” have been created. Given that there are 3 different specimens for each material and time under thermal stress. Therefore, the datasheets will be divided in the following groups, *Table 3*.

*Table 3. Datasheet groups*

PVC 90 seconds	PVC 105 seconds	PVC 120 seconds
PC 90 seconds	PC 105 seconds	PC 120 seconds

As well, each group is compared as well with every state of the DIE3 mold, as a reference.

Since the thermoforming process does affect the mold, there is an importance when it comes down to the order of thermoformed sheets. The methodology for thermoforming, which will inevitably affect the data results, has been the following:

Firstly, PVC sheets were thermoformed, following the pattern of 90 seconds under heat, 105, and then 120 seconds. Next, the same procedure was followed for PC. Therefore, the first PVC 90 sheets are expected to have the best accuracy since DIE have not been put under stress yet and, for last PC sheets, dimensional inaccuracies may be higher, as well as mold performance.

Therefore, more dimensional difference is expected to happen between the last PC sheets, where the DIE will already have been used during a multiple of times, rather than the first PVC sheets, where a tighter dimensional accuracy is expected to take place.

Following, it will be shown the base for each datasheet, which will include 3 main important points along the profile (usually one point around the center and one point in each side) and where will the data and the graph be located, as well as the color code for the analysis.



### 3.2. 3D Scan data obtain

The aim of the following section is to detail the methodology followed during the 3D Scan data obtaining, the collected data and results, as well as the equipment and the software used during the different trials done.

#### 3.2.1. Experimental work plan

The 3D scanning will be performed in the different DIE3 states, and as well, in one PC and PVC sheet of each temperature. Specifically, the bodies which will be 3D scanned, are detailed in *Table 4*.

*Table 4. 3D scanned bodies*

DIE3 – Before	PVC_90_S3	PVC_105_S3	PVC_120_S3
DIE3 – After	PC_90_S3	PC_105_S1	PC_120_S3

On top of that, DIE3 – Solidworks, which is the CAD design, will be compared with the different states of the scanned DIE3 body.

The steps to be followed are divided in two groups; the first one represents the data acquisition, performed with the 3D scanner EinScan Pro 2X; while the second one does represent the different software used to treat the data, from the same 3D scanner software, and to the final CAD software which will allow comparing results.

Therefore, the experimental work plan for 3D scanned body is basically to scan the body and find the right tools to treat those data, compare DIE3 bodies, as well as each PVC and PC sheet with regards to the mold.

Besides, it has to be stated that PC and PVC sheets used in comparison are cut in half, as shown in *Illustration 23* due to other tests and analysis performed on them.

### 3.2.2. Data analysis

The equipment used is the 3D scanner EinScan Pro 2X, shown in *Illustration 5*, whose software is the SHINING 3D.

Its main parts are the following:

- Handheld scan placed over a tripod, which scans the body object,
- Turning plate. It supports the body object to be scanned, and it turns the body 360° according to the parameters defined,

It does work by creating a triangular shaped mesh body, by each rotation of the turning plate, ending up with the closed surface once the scan has been performed.

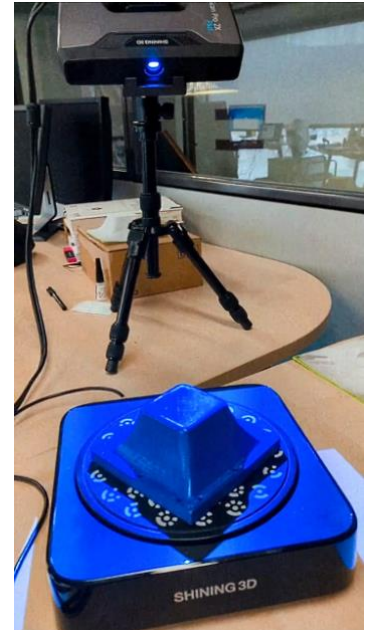
Even though the surface is closed once the first scan is performed, it will be needed an extra one to close the body, since the base will not have been analyzed yet. Therefore, there is a first work in SHINING 3D of adjusting two different closed surfaces in order to create one whole mesh body.

The 3D scanner adjusts the data up to a  $\pm 0.04$  mm of accuracy, and even though it is not as much as the CMM machine, it allows a high accuracy study of the scanned surface body.

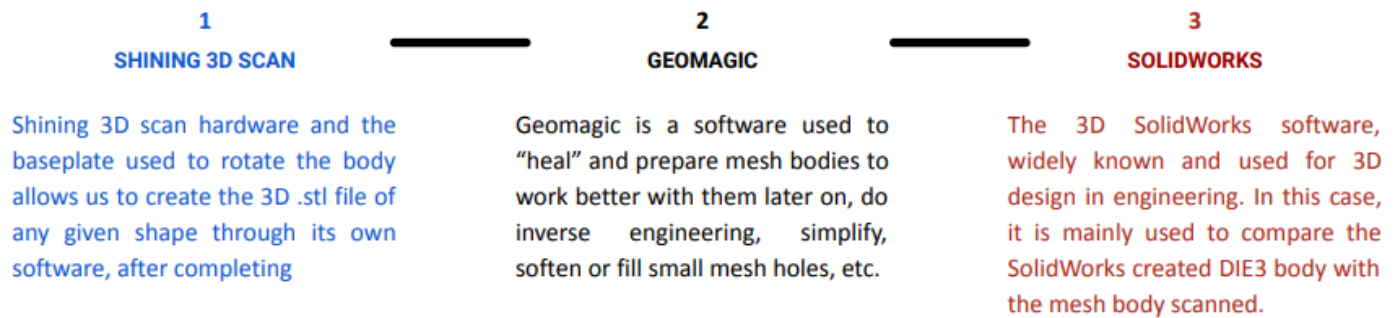
Once it has been performed, the data will be available to export to other software to treat the data which will lead to a dimensional comparison of bodies.

Following, a brief explanation of the different software used and the path for data treatment for better understanding, as well as a wider explanation of each software role in it, *Illustration 6*.

- Shining 3D -> 3D scan integrated software
- Geomagic -> A mesh builder, optimizer and reverse engineering software for converting 3D scan data into feature-based and editable solid CAD models.
- CAD working software -> After different tryouts with Solid Edge by Siemens, Autodesk Fusion 360 by AutoDesk and Solidworks by Dassault Systèmes, the latter has been finally used as the software to treat data, establish the converted 3D scan CAD model created and compare design models with 3D scanned bodies.



*Illustration 5. 3D scanning DIE3 after thermoforming.*



*Illustration 6. General software usage overview*

### 1. Geomagic Essentials

As already defined, Geomagic is a specialized software in mesh body treatment and post 3D scan analyzer and solver. The importance of it, is that even though SHINING 3D does an initial “body mesh healing” allowing the user to fill holes, once the meshed body is opened through Geomagic, many smaller wholes can be seen and need to be closed, in order to treat and compare the body correctly later on.

### 2. SolidWorks

The latter software to be used is CAD analyzer software. In this projects case, Solidworks has been found as the easiest software to work with.

Solidworks, apart from all the different possibilities of 3D design, it also allows working with the bodies created and defined, define coordinates systems and geometric shapes for mesh bodies and comparing them.

Firstly, it has to be explained that Solidworks does have a tool for directly compare similar bodies. However, the comparison is not direct since we are working with a 3D scanned mesh body and not a 3D Solidworks shaped and designed body.

Therefore, different plane surfaces, points and a coordinate system should be created from the mesh body and its facets in order to compare correctly the bodies. Following this process, it can either be compared two meshed bodies or one Solidworks defined body and one 3D scanned meshed body.

### 3.2.3. Expected results analyses

Similarly to the CMM machine profiles analyzed, a “datasheet” has been created. In this case, it is just the ensemble of the two scanned bodies in comparison in their 3D shaped color pattern and its legend, where each

triangular face created by the 3D scan does have a different color, representing a different height difference between bodies.

### **3.3. CMM data and 3D Scan data comparison**

The aim of the following section is to detail the methodology followed during the comparison of CMM machine data and 3D Scan data.

#### **3.3.1. Experimental work plan**

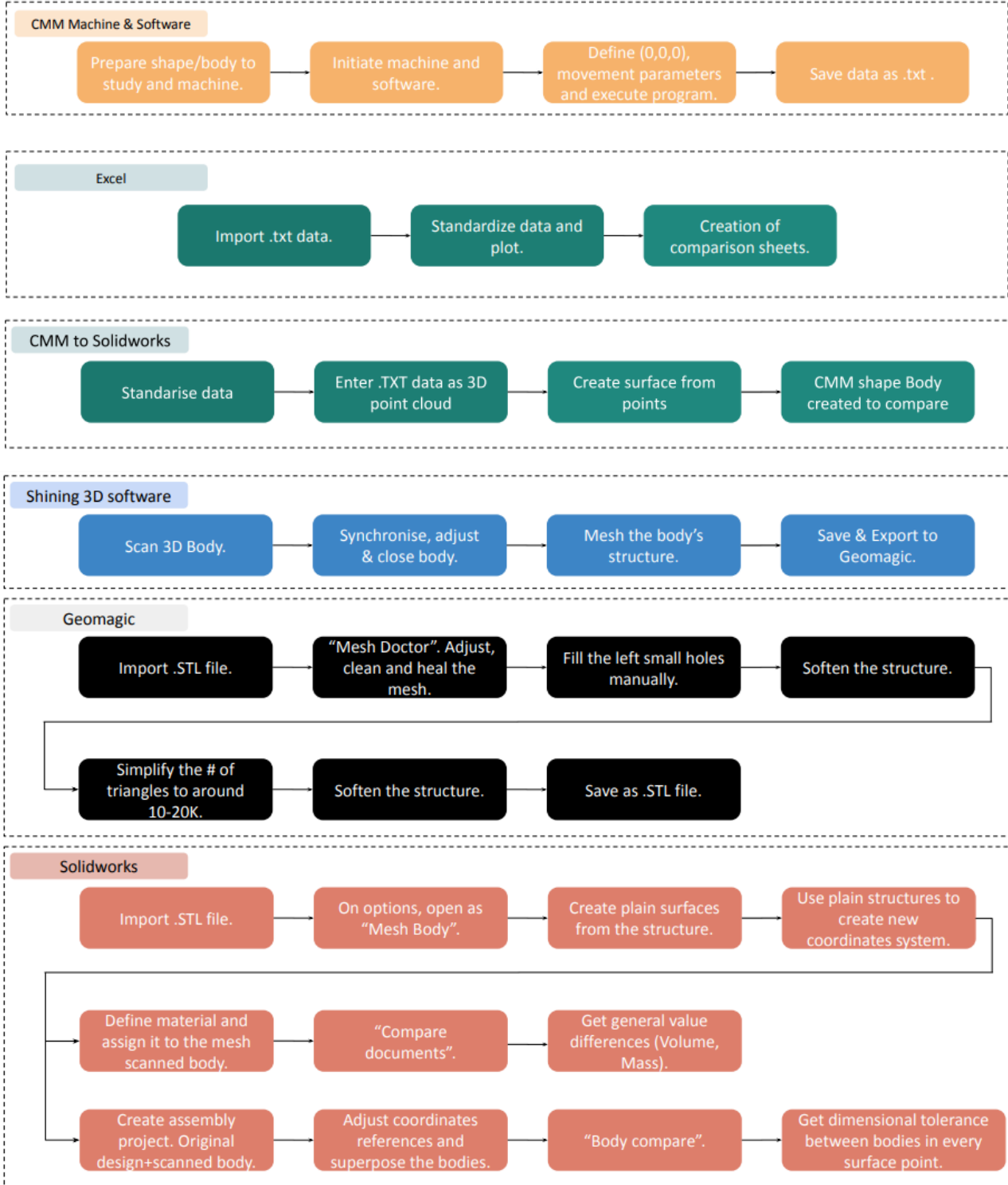
While the CMM machine does give coordinates of a planar surface, 3D scan does give a whole meshed body to be treated. Therefore, the difficulty of standardizing a methodology for the right comparison of both methods lies on the capacity of the treatment usage done by the different software.

#### **3.3.2. Data analysis**

Therefore, given the complexity and uselessness of exporting and examining a 3D scanned body into a two-dimensional space to analyze each and every section, the only option is to export the .txt file from the CMM machine into a CAD software, create a body from it by emulating the surface of the mold or the PVC/PC sheet, and comparing it with the 3D scanned body, which has been the final solution found.

### 3.4. Project flow diagram recap

To better comprehend the procedures that have been described in the methodology, a flow diagram is presented, *Process diagram 2*. It contains the key information and should allow the reader to synthesize all the information above.



*Process diagram 2. Data protocol treatment for profiles*

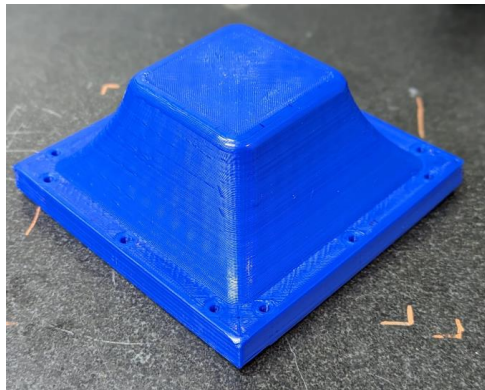
## 4. Results and discussion

In this chapter, the results and conclusions from the experimental work previously described are going to be presented. This section is sorted in the same order as the already presented methodology in section 3.

Since once a methodology of data treatment is found for the first body, then it is later on used and adapted for the other bodies, there is an intrinsically correlation between results exposition. Therefore, it has been decided to detail the steps followed to get the data results for the first treated body, the DIE3, *Illustration 7* (exactly how it has been scanned, data taken from CMM machine and then the multi-software usage process for comparison, which eventually has led to a full body 3D comparison) and then, for other bodies, PVC and PC sheets, *Illustration 8* and *Illustration 9*, the results are focused on the data comparison.

The results order, therefore, are presented following the order specified besides:

1. Issues concerning to DIE 3 printing analysis.



*Illustration 7. DIE 3 body of study*

2. Analysis on sound thermoformed PVC sheets



A)



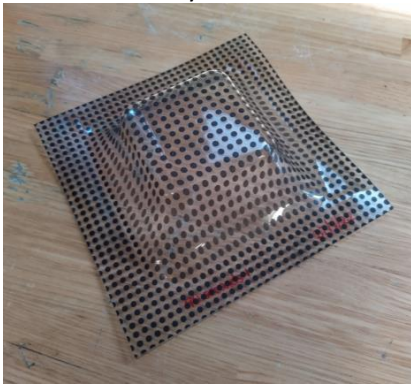
B)



C)

*Illustration 8. A) PVC 90; B) PVC 105; C) PVC 120*

### 3. Analysis on sound thermoformed PC sheets



A)



B)



C)

*Illustration 9. A) PC 90; B) PC 105; C) PC 120*

## 4.1. DIE 3

This section presents the different data treatment followed for the dimensional study for the DIE 3. It comprehends both the CMM Machine and 3D Scan usage.

The analysis which has been performed, is mentioned below:

- 3D printing process accuracy (comparison of DIE Design state – DIE Before deformation)
- Thermoforming process wear (comparison of DIE Design state – DIE After deformation)
- DIE different states comparison (via Excel and via SolidWorks)

Although the analysis between different DIE3 states is the key issue of this point, it has to be pointed out that the methodology of obtaining the data via CMM and 3D scan, as detailed before, is the main objective of this project. Therefore, being the DIE3 the first object of study in the results and before going directly into the different analysis for the DIE3, following is detailed the step-by-step guide to obtain and treat the data, both from CMM and from the 3D scan in order to study and do the different analysis.




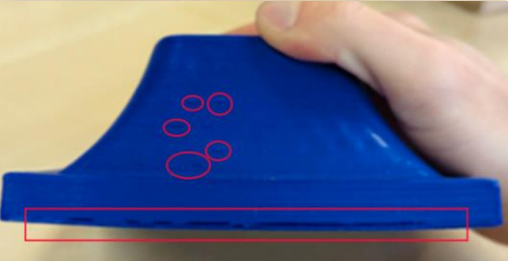

#### 4.1.1. DIE 3 Defects found – naked eye observation

Due to the thermoforming process, the DIE3 has suffered deformations due to its use during the process and heat exposure, as well as other factors such as defects while doing the vacuum on the process, uneven cooling of the surface, the shrinking effect which could take place after the thermal exposure, etc.

These defects can affect the dimensions of the DIE3 when analyzing and they should be controlled in order to make sure they do not compromise both the thermoforming of the PC and PVC sheets nor the mold integrity itself.

Below, the mainly defects found are matched with photos in order to exemplify them, *Table 5*.

*Table 5.- DIE3 after thermoforming defects.*

MOLD PHOTO	DEFECT
	<p>Even though the body should remain plain with regards to the table, there is a curvature in the bottom part of the body, by which the whole base surface is affected.</p>
	<p>Besides of the curvature in the base surface, there can also be seen broken layers of the material at the bottom. Broken layers can also be seen, in smaller samples, in other parts of the DIE.</p>
	<p>Also, given a topside view, it can be seen that there are a multitude of wrinkles which have appeared, due to the thermal stress and the movement of layers during the thermoforming process.</p>

#### 4.1.2. CMM Machine data obtention and comparison

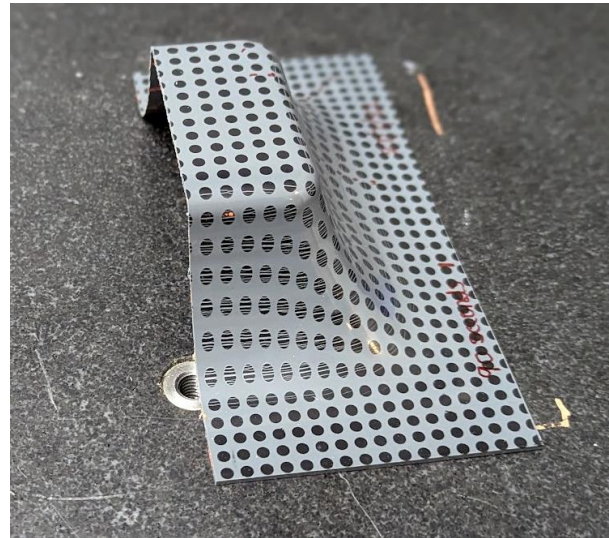
**Note.** All the information detailed is also valid for PC and PVC sheet data obtention.

Mainly, for obtaining the CMM machine data, the DIE3 was positioned in the machine framework, and then 0.1mm steps were defined, for a linear positioning. Therefore, the machine did move from one side of the DIE to the other, detecting a point each 0.1 mm and then plotting its coordinates.

Following, it can be seen both an image from the CMM machine taking data and, as well, the result from the CMM software, *Illustration 10*.



A)



B)

*Illustration 10. A) CMM machine working on a PVC thermoformed sheet; B) PVC sheet cut.*

Once the whole profile is performed, regardless of it being a DIE3, a PC or PVC sheet, the data has been exported as a “.txt” file and then imported into an excel file, to run the different comparisons and analysis with it. Also, “.txt” data profiles can be imported into a Solidworks file, which has allowed the comparison between the CMM machine profiles and 3D body scanned data.

### 4.1.3. 3D Scan data obtention and body comparison

**Note.** All the information detailed is also valid for PC and PVC sheet data obtention and comparison.

The definition of the procedure to scan a body, treat the meshed body data and compare it, is detailed in *Annex VI – Manual document to scan bodies* .

Solidworks has been used as the comparison platform. As stated in 3.2.2, Solidworks does provide the needed software in order to compare the scanned sheets, the DIE3 mold design state, which was initially designed in

Solidworks, and also, excel and .txt data obtained in the CMM machine can also be applied in the software in order to compare it with the same 3D scan objects. The process followed step-by-step for comparing bodies, is detailed in

Annex VII – Manual document to compare bodies.

#### 4.1.4. 3D printing process accuracy

The first study performed with respect to DIE3 is the comparison of the design DIE3 model with respect to the DIE3 before deformation (DIE 3 – Solidworks vs. DIE 3 – Before), in order to determine the dimensional accuracy for the 3D printing process. In this case, CMM Machine has been the hardware used while Mitutoyo software and excel have been the software used in order to compare correctly both bodies.

Given the geometry of the DIE, which is symmetric from both x and y axis, a CMM data whole profile section has been used as the DIE3 – Before data. In X value, every 0.8mm one data point was taken and then the whole profile was then exported as .txt to an excel sheet.

As DIE3 – Design state data, the exact same profile data has been used, using Solidworks. In this case, since solid works does not give you all the exact points of a given section by default, it has been needed to examine and measure manually each and every point from the software in order to compare the exact same point, using the same rule as the CMM machine (one data point every 0.8mm following x axis).

Then, both data were compared in an excel sheet,

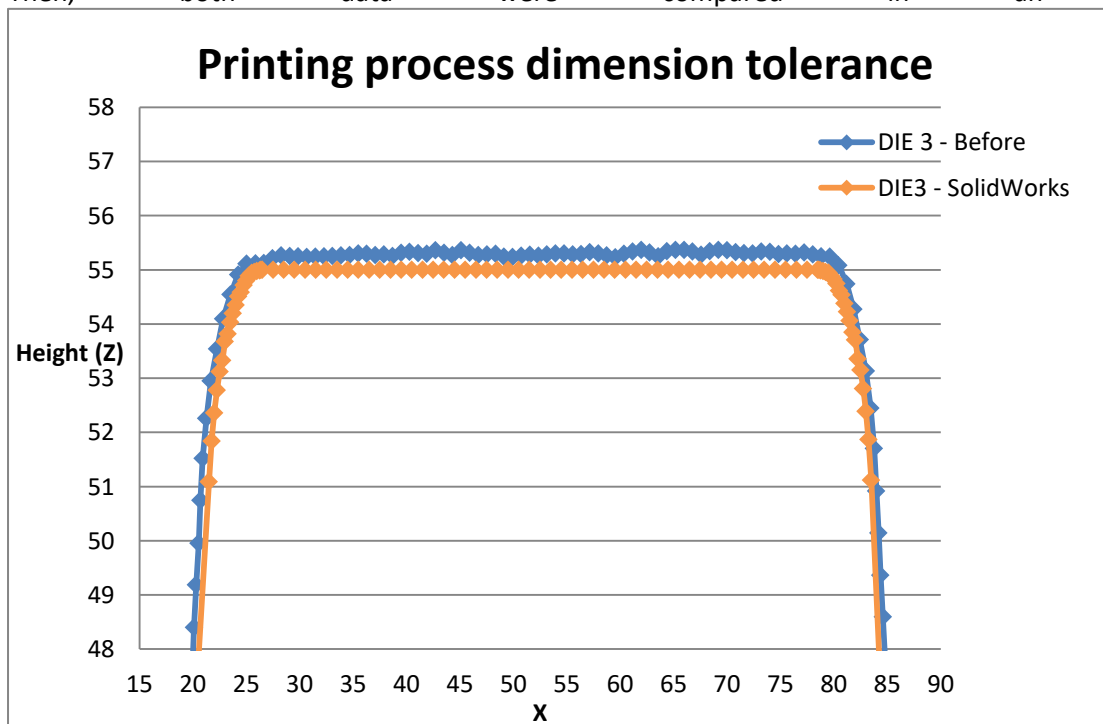
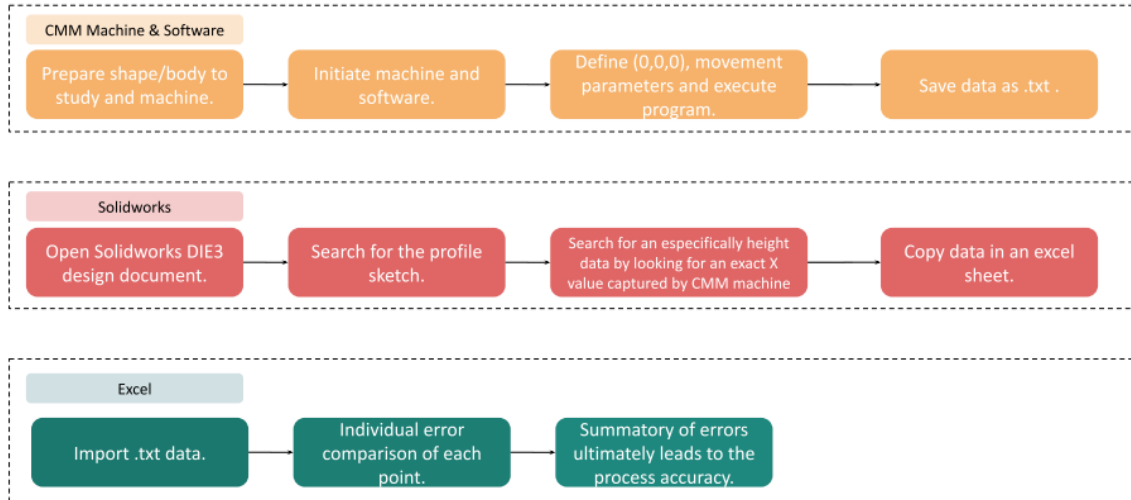
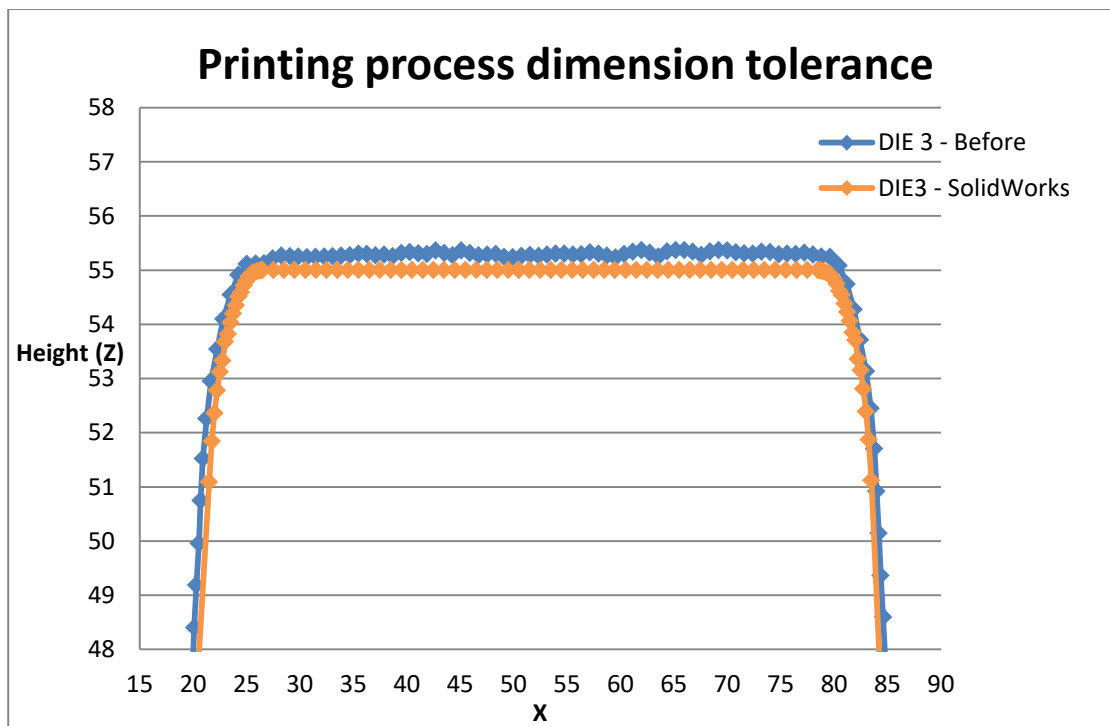


Illustration 11, where data values were standardised and then the comparison process of +200 points was performed. As a result, the total sum of the errors gives a **2.014%** of error, which represents a total dimension

accuracy for the 3D printing process of 97.986%. The mean value of the difference between the two states along the profile is  $\pm 0.58593\text{mm}$ , and the detailed information is shown in *Table 6*. Besides, the exact data protocol followed in order to perform the accuracy process, *Process diagram 3*, including Solidworks data extraction, and also the body comparison between DIE3 – Solidworks and DIE3 – Before, in *Illustration 12. DIE 3 comparison. Each facet height difference.*



*Process diagram 3. 3D printing dimensional accuracy process diagram.*



*Illustration 11. 3D printing dimensional accuracy process.*

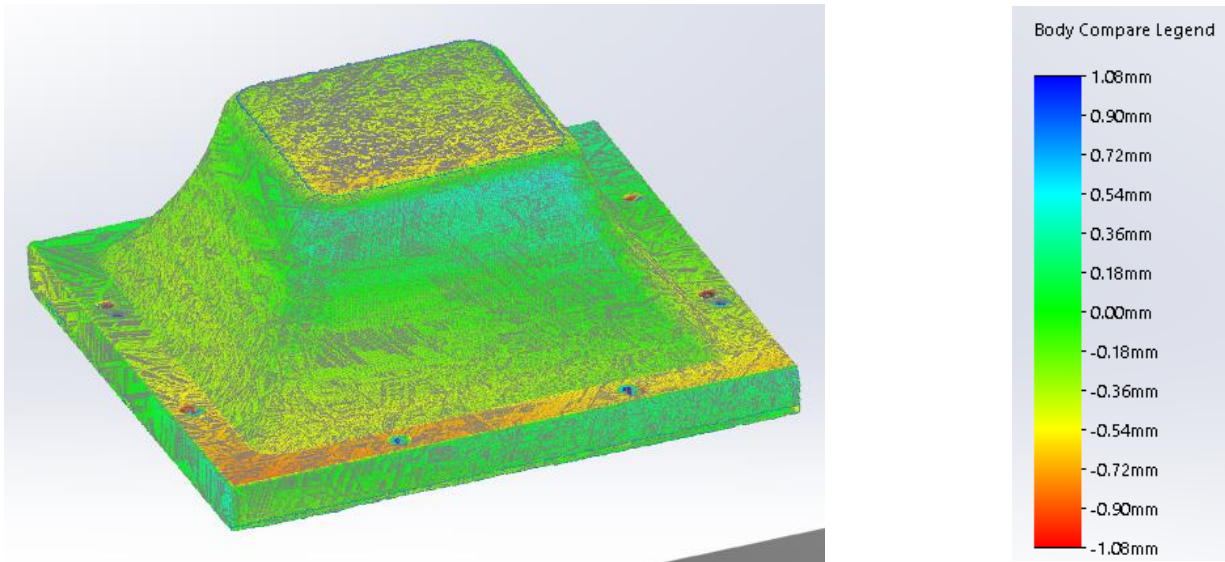


Illustration 12. DIE 3 comparison. Each facet height difference.

In this case, the dimensional comparison process is simpler and does not require selecting the comparison points, just defining the surfaces to compare and position the bodies using the correct tools. Also, the Solidworks comparison does not give a whole profile section comparison but a whole body 360° view data height difference. It can be seen, also, that the height difference varies to a maximum of  $\pm 1.08\text{mm}$  (colour code from blue to red) but actually most of the data is comprehended in the range of  $\pm 0.54\text{mm}$  (colour code in green).

Table 6. Printing process dimensional tolerance

Values in mm	CMM Machine	SolidWorks Comparison*
<b>Maximum difference</b>	1.69676	1.08
<b>Mean value</b>	0.58593	0.54
<b>Error percentage</b>	2.0140%	1.8561%

Since CMM Machine does allow us to have the discrete data of each and every point analysed, the SolidWorks comparison does not. Therefore, even though it is not possible to extract each facet data and take the exact % of dimensional accuracy between bodies, the tolerance set up in Solidworks of 1.08mm has been used as maximum difference and 0.54mm (part of the body in green), has been used in order to calculate an approximate error percentage.

Also, it is needed to be said that Solidworks comparison maximum value of comparison is 1.08 but has left values above and under the value, which are represented in black in *Illustration 12* (almost none), while the CMM machine has taken into account each height difference, up to the maximum of 1.69976 shown in *Table 6*.

Even though, the data analysis between Solidworks and the CMM machine does have coherence and it can be stated that the 3D printing process accuracy does create a minimal error with regards to the designed body.

#### 4.1.5. Thermoforming process wear

In comparison with the 3D printing process accuracy, in the thermoforming process wear, a higher dimensional difference is expected to take place. Therefore, extra data has been taken and the pattern studied is the following. As well as with the prior analysis, CMM machine and its data has been used and then treated and compared via Excel. As well, the 3D Scan has been used to scan the DIE3 different states (before and after thermoforming) and afterwards they have been compared.

For comparing the bodies, DIE3 – Before has been taken as the reference body, while DIE3 – After has been used as the comparison body.

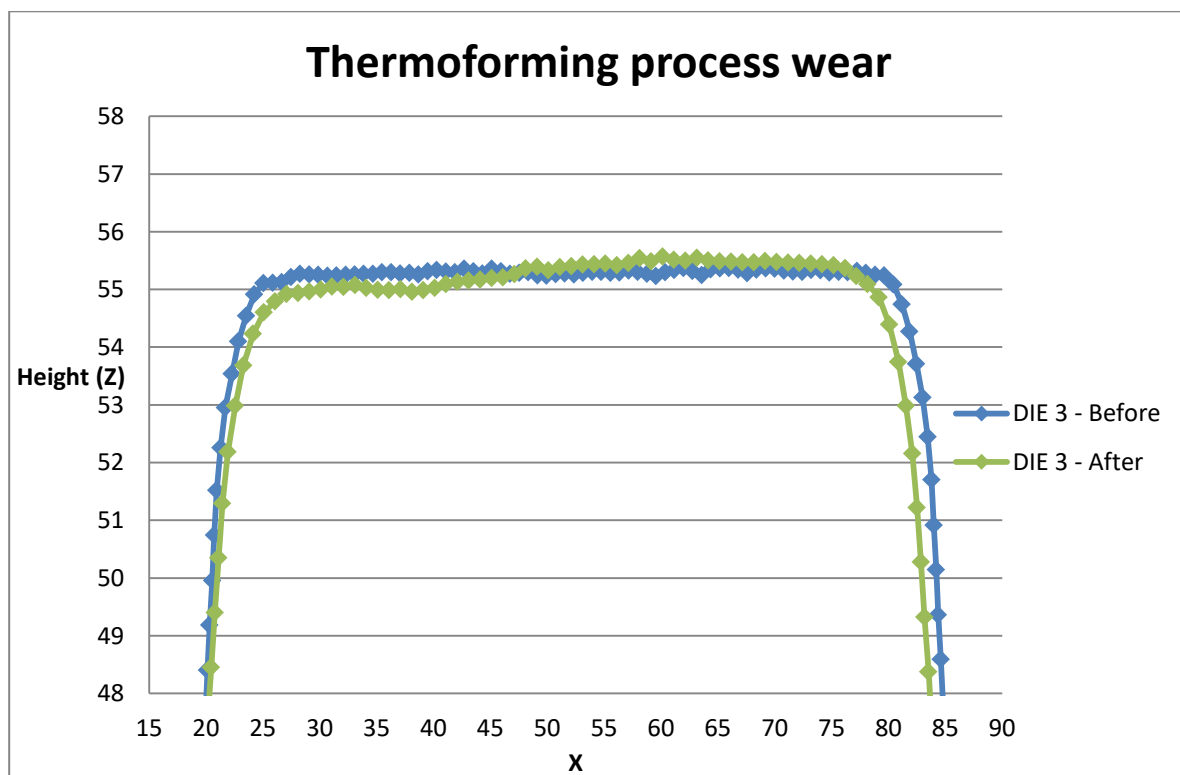
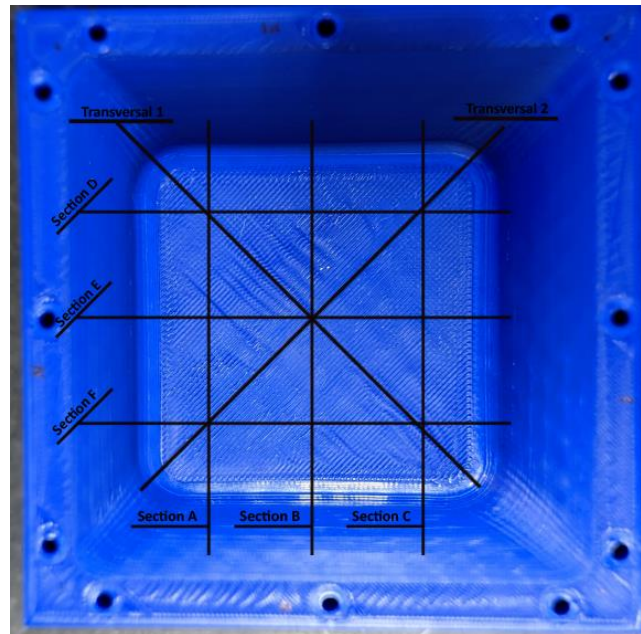


Illustration 13. TF process wear, comparison with CMM machine

It has been found that, dimensionally speaking, naked eye observation in *Illustration 13*, the mold has followed different patterns and while in some zones it has shrunk, having a smaller height, in other zones the material has dilated. It is attributable to the thermal and shear stress of the DIE3 during thermoforming the PC and PVC Sheets. Since the deformation and height loss is neither continuous nor even, different sections have been studied. This way, it has been possible to examine better the tolerance of the 3D printed material during the thermoforming process.

A total of 8 different sections have been taken using the CMM machine, and it has been emphasised on the topside zone of the DIE. As well, since the 3D printer does follow a printing build orientation, three sections have been taken following Y axis (named as: Sections A, B and C) while three more have followed the X axis (named as: Sections D, E and F), *Illustration 14*. As well, two different crossed sections have been analysed, named as Transversal 1 and Transversal 2 sections.



*Illustration 14. Topside sections analyzed*

Two different orientations have been studied separately, in order to map correctly regarding the 3D printing build orientation:

- Orientation 1: It refers to sections A, B and C.
  - o Upper zone: Lowest points were found.
  - o Center: Highest points were found.
  - o Down zone: Higher points than the reference
- Orientation 2: It refers to sections D, E and F.
  - o Left-side: Lowest points were found.
  - o Center: Highest points were found.
  - o Right-side: Points are closer to the reference, in some cases almost equal.

Following, it can be seen an image plotting the different sections created using the CMM machine, as well as their comparison with regards to the DIE3 – Solidworks reference body, while in the left part, it can be seen the SolidWorks comparison between scanned bodies, *Illustration 15*.



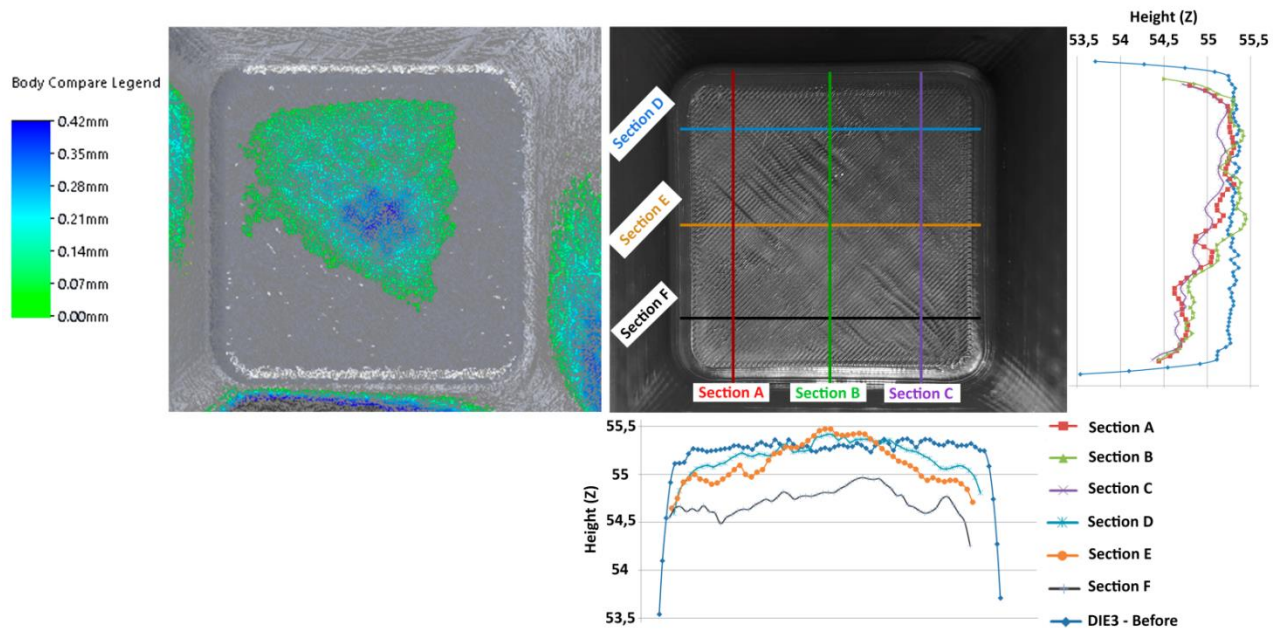


Illustration 15. Different sections comparison

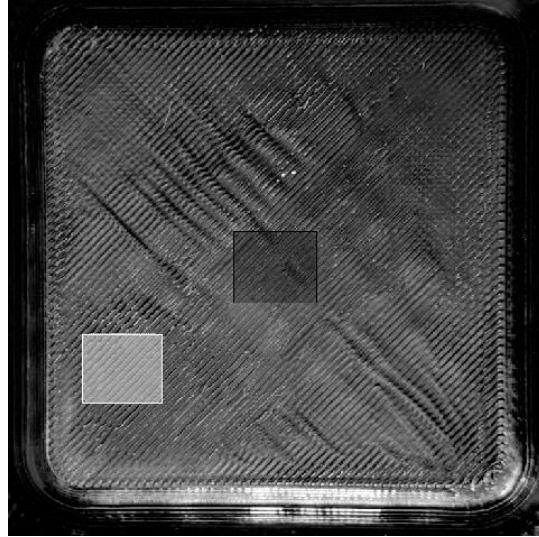
Therefore, after mapping the topside surface as a whole, the following deductions have been done:

- As stated before in *DIE analysis: Thermoforming process wear*, after seeing the results, it can be stated that the mold itself has not had an evenly deformation, where local zones have developed a shortening effect while others have dilated. Middle and center zones have dilated and got bigger, while the sides of the topside and specifically the left-side and upper-zone, have developed a shortening effect.
- One explanation of it could be that the 3D printed layers may have slide from one zone to another due to the thermal wear. Because of it, it has been studied how many layers of the 3D printing process may have either slide to a closer zone or either got removed because of the thermal wear itself. It has been found that, regardless of if they were dilation or shrunk driven values, a maximum of 4 top layers have been moved in one particular point, giving always a precision of under 1mm of difference regarding the comparison body, the DIE3 – Solidworks.(In *Annex III.- 3D printed mold (DIE3)* there is the definition of the 3D printing parameters, where it can be found the top and external wall total layers)
- As stated before, zones at which the mold does suffer the most are on the left-side, where there appear the greatest data point depressions, and at the center zone, where the highest points can be found, in comparison to the reference body. On the right-side, there are also mainly depression points, even though the height difference is smaller with regards to the left-side.
- The left side of the mold does not only refer to the data point depressions but, as well, does refer to the highest height difference between the reference and the body under study and therefore the zone which

suffers the most from the thermal exposure of the mold during thermoforming. This extract can be easily explained looking at

- Around the right-side in orientation 2, the deformation and shear created by thermoforming is minimal.
- The lowest point is found on section F, while the highest point is found on section E, as shown in

*Illustration 16.*



*Illustration 16. Lowest point zone in white. Highest point zone in black.*

As it can be seen in the recent illustration, folding/warpages have appeared in the DIE3 top surface. Despite of it, the points measured do not show a substantial increase or decrease in height with regards to those zones.

In the left side of the following image, the Solidworks comparison can be seen, where the different DIEs have been compared (DIE3- Before and DIE3-After) and the zones which appear to be higher after thermoforming are colored in either green or blue, following the color legend. This Solidworks comparison has been done by scanning the DIE3 both Before and After thermoforming, and then comparing them bodies via Solidworks. In section *Annex VI – Manual document to scan bodies*, the whole procedure for scanning and comparing the bodies is detailed; here, only the analysis of the data obtained is being explained.

The left side of the mold does not only refer to the data point depressions but, as well, does refer to the highest height difference between the reference and the body under study and therefore the zone which suffers the most from the thermal exposure of the mold during thermoforming. The quantified difference can be found in *Illustration 20. DIE 3 Different states comparison.*

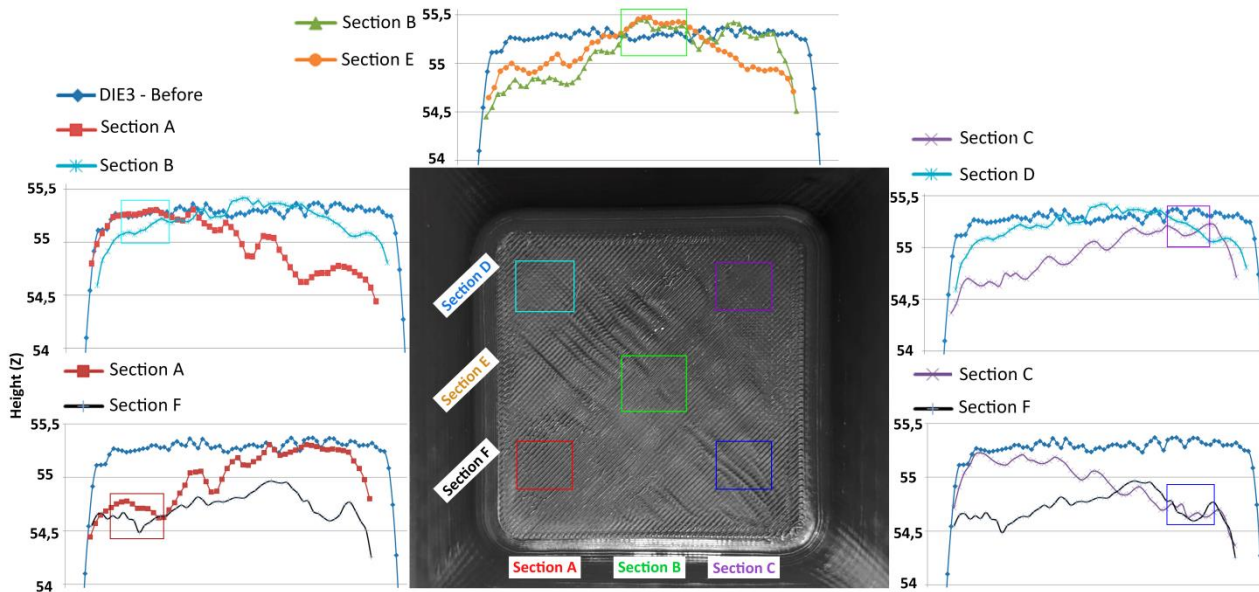


Illustration 17. Height in exact zones, comparing different profiles

Although process wear has already been detailed and studied through CMM machine comparing profiles, focusing on detailing the top surface shape and shear; with the SolidWorks, it can be seen the 360° view of the whole DIE3 structure shear, *Illustration 18*.

After values, the body definition of 10000 facets and the body comparison.

Following, it is shown the results for the 3D printing dimensional accuracy comparison, using both 3D scanned bodies (DIE3 – Before and DIE3 - After). In this case, the total facet counts goes to 3.5 million.

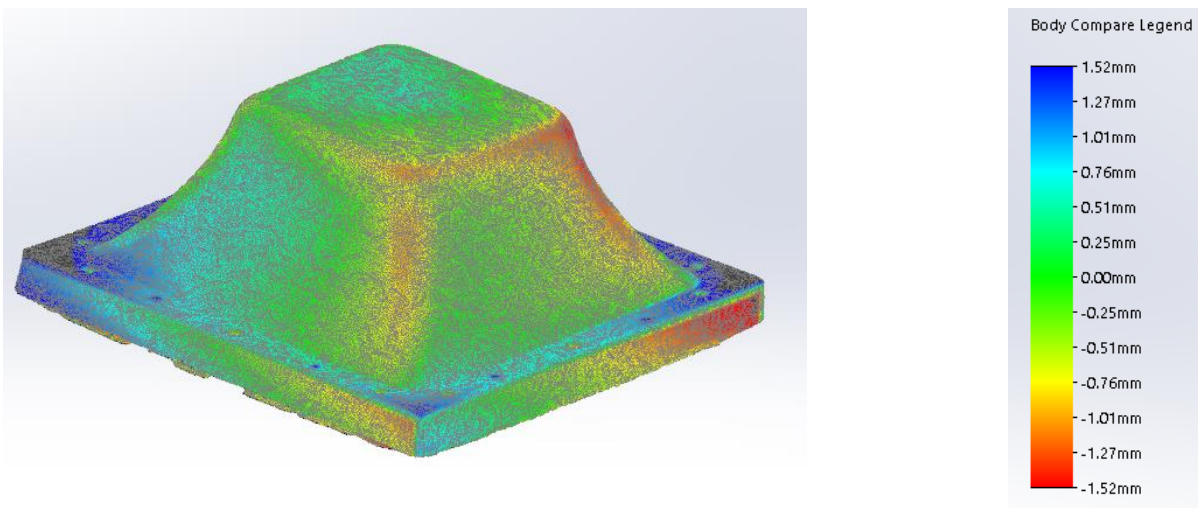


Illustration 18. DIE3 - Before & DIE3 - After. Each facet height difference.

Using the same methodology as in 4.1.4, for studying the Solidworks dimensional tolerance, the height difference varies to a maximum of  $\pm 1.52\text{mm}$  (colour code from blue to red) but actually most of the data is comprehended in the range of  $\pm 0.76\text{mm}$  (colour code in green), *Table 7*. It is needed to be said, as well, that while SolidWorks comparison is on the whole body, the CMM Machine profiles studied, in this case, do focus on the topside data, and hereby the difference in the values of the table is understandable.

It can be seen that the corners do have a higher dimensional difference, which could actually be due to the vacuum during thermoforming, or due to that those zones are the ones which do experiment a higher stress, due to their positioning in the geometric of the DIE3.

For the bottom height difference, it is understandable due to the mold defects already explained in 0.

*Table 7. Thermoforming process wear dimensional accuracy*

<i>Values in mm</i>	<b>CMM Machine (topside)</b>	<b>SolidWorks Comparison*</b>
<b>Maximum difference</b>	0.74693	1.52
<b>Mean value</b>	0.2604	0.76
<b>Error percentage</b>	0.89506%	2.6123%

#### **4.1.6. DIE 3 different states comparison**

When it comes down to the comparison of all the DIE3 states, it has been managed to include the CMM machine, 3D Scan and SolidWorks data in one same comparison. After many tryouts, an optimized pathing has been created which allows to represent and compare dimensionally all the different data.

Following, it can be seen:

- Firstly, an illustration which works as an Index to understand the “data excel sheet”, *Illustration 19*.
- Second, the CMM data profiles and Solidworks extracted data to compare all DIE3 profiles, *Illustration 20*.

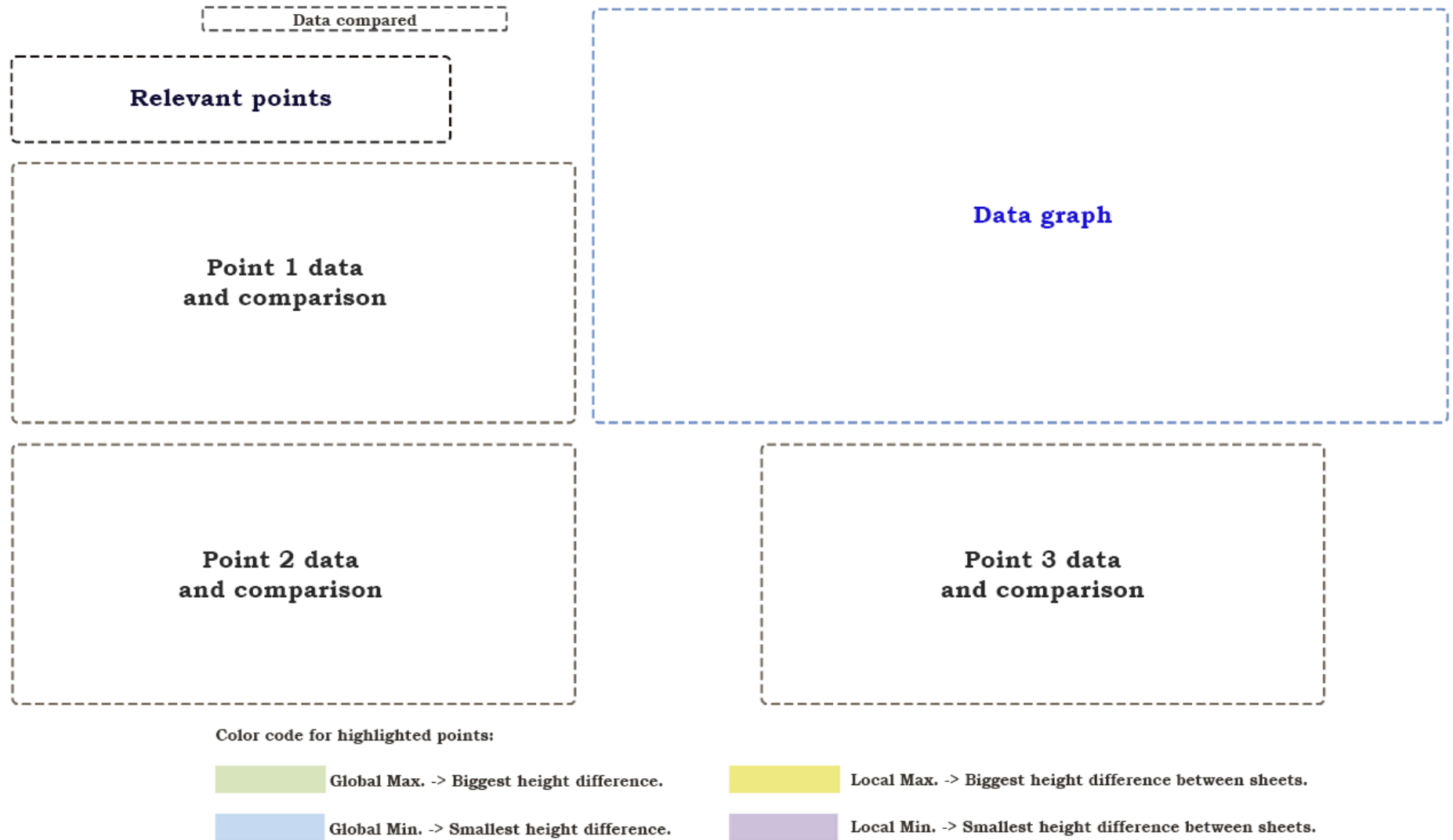


Illustration 19. Data comparison sheet explanation.

Data comparison - DIE 3

	(x)	Reason
Point 1	37	Left-side / Lowest
Point 2	54	Around the middle of the top side
Point 3	72	Right-side

Point 1

	Original (x)	Standardised (x)	Height (z)
DIE 3 - Before	96,48197	37,65469	42,7741
DIE 3 - After	146,0619	37,60005	41,96164
DIE 3 - SolidWorks	47	37,5	43

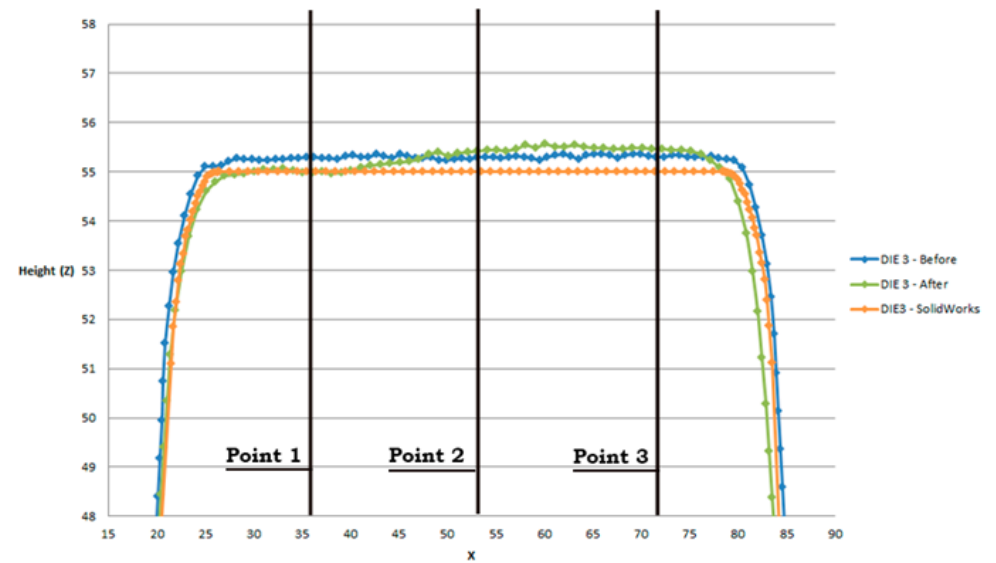
	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
DIE 3 - Before		0,81246	-0,2259
DIE 3 - After	-0,81246		-1,03836
DIE 3 - SolidWorks	0,2259	1,03836	

Point 2

	Original (x)	Standardised (x)	Height (z)
DIE 3 - Before	113,35245	54,52517	42,79441
DIE 3 - After	163,08201	54,62016	42,45003
DIE 3 - SolidWorks	64	54,5	43

	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
DIE 3 - Before		0,34438	-0,20559
DIE 3 - After	-0,34438		-0,54997
DIE 3 - SolidWorks	0,20559	0,54997	

DIE 3 - Comparison



Point 3

	Original (x)	Standardised (x)	Height (z)
DIE 3 - Before	131,01169	72,18441	42,79005
DIE 3 - After	181,13457	72,67272	42,44978
DIE 3 - SolidWorks	82	72,5	43

	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
DIE 3 - Before		0,34027	-0,20995
DIE 3 - After	-0,34027		-0,55022
DIE 3 - SolidWorks	0,20995	0,55022	

Illustration 20. DIE 3 Different states comparison.

It has been decided to check 3 different points, and while the data has already been explained by most of the zones, defining the zones at which the height is higher by each body, the CMM section viewed data does provide an even more accurate result and the exact value of the height at each point. Therefore, the capability of studying desired points and places around the body is best with this tool.

The three profiles examined are situated in the middle section of the DIE3, neither around the corner nor edges. It can be deduced, from the comparison of the bodies with regards to the final composition, DIE3 – After, that around “Point 1”, *Table 8*, or left side of the section analyzed, there appears the zone at which the body has shrunk more due to thermal stress, while the center-right part of the body (between “Point 2” and “Point 3”), there appears a dilated zone with regards to the DIE 3 – Before.

The chosen points are not only because of their positioning with regards to the geometry of the DIE3, but also because of their profile height, as explained in “Relevant points” in the prior illustration.

*Table 8. DIE 3 different states – Dimensional accuracy*

<i>Values in mm (%deviation)</i>	<b>DIE 3 – SolidWorks</b>	<b>DIE 3 – Before</b>	<b>DIE 3 - After</b>
<b>DIE 3 – SolidWorks</b>	-	0.81246	-0.2259
<b>DIE 3 – Before</b>	-0.81246 (2.7926%)	-	-1.03836
<b>DIE 3 - After</b>	0.2259 (0.7765%)	1.03836 (3.5691%)	-
<b>Mean value</b>	0.475233		
<b>Total error percentage</b>	1.63350%		

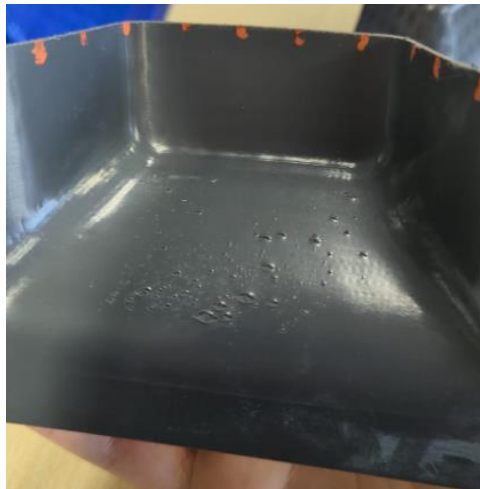
## 4.2. PVC Sheets data analysis

This section presents the different data treatment followed for the dimensional study for the different PVC sheets. As well as what happened with the DIE3, it comprehends both the CMM Machine and 3D Scan usage.

The analysis performed focus on the study of the different PVC sheets, classified by time under thermal stress while thermoforming, with regards to the mold itself, studying the dimensional accuracy.

### 4.2.1. PVC Sheets defects patterns

On all three PVC 90 second sheets, they do appear to shape perfectly according to the mold, with no defects on external surfaces, and correct height. Nevertheless, a small gap is appreciated at the bottom, where a small separation has been found between the mold and the thermoformed sheet. Unfortunately, there is a defect found in the internal side of PVC\_90\_S2, which does have bubbles on the internal face, *Illustration 21*, the one touching the mold. Also, when comparing profiles, PVC\_90\_S2 has been discarded due to a height difference, led by a vacuum misconducting, which has ended up shaping the thermoformed sheet badly and not sticking it to the mold correctly.



*Illustration 21.- PVC\_90\_S2. Internal bubbles*

With PVC 105 seconds sheets, the first defects do appear. On first sheet, even though the profile which data was taken from is OK, there actually is a bump in a part of the topside, *Illustration 22*.

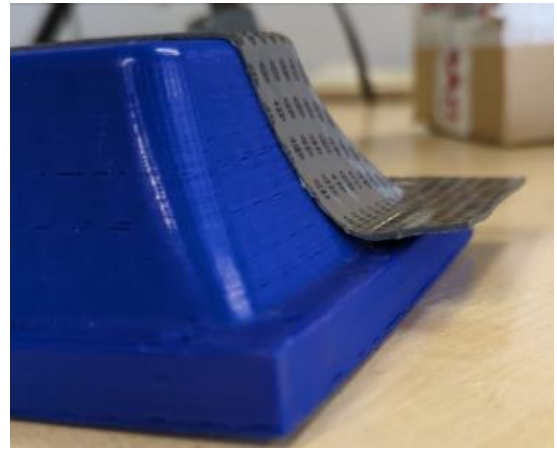
On the second sheet, there is a central-zone bump, and even more accentuated on left-center zone. As well, looking closely on the internal face of the thermoformed sheet, black dots do appear to be more present, varying even more the topside height.



On third sheet, a gap is appreciated at the bottom between the mold and the thermoformed sheet, where the sheet is not in contact and does have lesser height.



A)

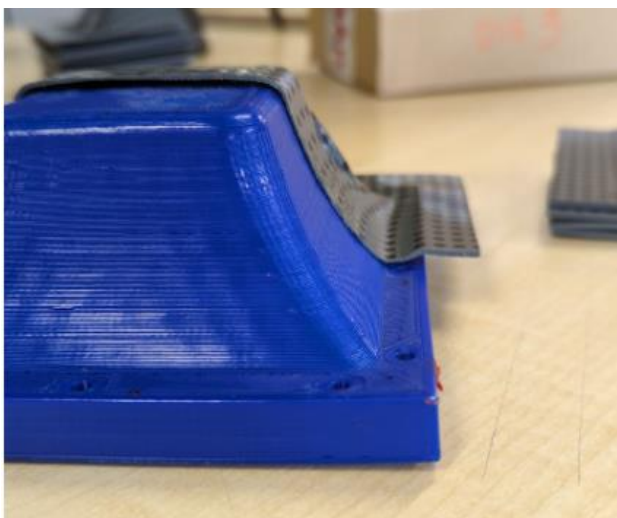


B)

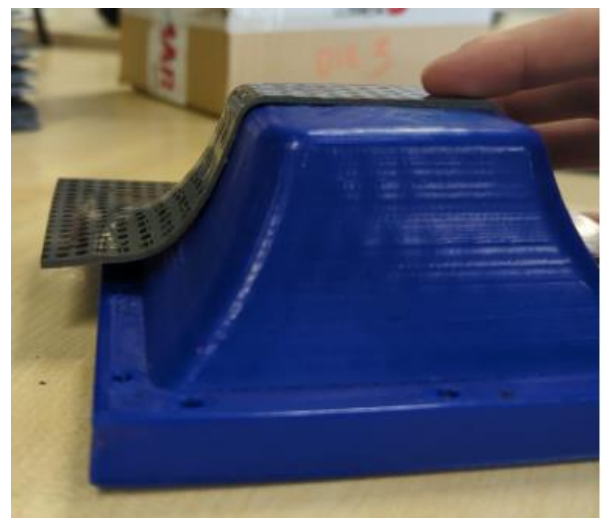
*Illustration 22. A) PVC\_105\_S2. Topside bump; B) PVC\_105\_S3. Height gap at baseline.*

With PVC 120 seconds sheets, there are more problems than on previous ones. On sheet one, there are wrinkles or folding on one side, which does create a topside bump, on the wrinkle side, displacing layers. This wrinkle does appear in both external faces of the sheet, *Illustration 23*, the one in contact with the mold and the other one.

Sheet two does have a separation between the mold's bottom side and its laterals, which may mean that thermoforming was not performed correctly due to, for example, bad vacuum, which would have done the sheet to cool faster, making it contract. On sheet three, there is bump topside again.



A)



B)

*Illustration 23. A) PVC\_120\_S1. Topside bump + wrinkle; B) PVC\_120\_S2. Bottom height difference.*

As a résumé, a defect patterns found for PVC sheets has been performed, in *Table 9*.

*Table 9.- PVC defects patterns.*

SHEET	DISPLACEMENT OF LAYERS	BUMPS	BUBBLES	HEIGHT DIFFERENCE AT THE BOTTOM / BASE	WRINKLES / FOLDING
PVC 90S1	-	-	-	X (Small gap)	-
PVC 90S2	-	X (internal face)	-	X	-
PVC 90S3	-	-	-	X(Small gap)	-
PVC105S1	-	X	-	-	-
PVC 105 S2	-	X	-	-	-
SHEET	DISPLACEMENT OF LAYERS	BUMPS	BUBBLES	HEIGHT DIFFERENCE AT THE BOTTOM / BASE	WRINKLES / FOLDING
PVC 120 S1	X	X	-	-	X
PVC 120 S2	-	-	-	X	-
PVC 120 S3	-	X	-	X (?)	-

Besides all the physical problematic and defects found just by overlapping the PVC sheet over the DIE3 after thermoforming takes place, the height patterns of the thermoformed sheet has been studied.

#### 4.2.2. PVC Sheets data comparison

The process for taking out the data for the PVC sheets with the CMM machine has been the same as with the DIE3. Following, there is shown an example of the data regarding the comparison of the three PVC 90 second sheets with regards to the DIE3 – After.

As stated in the methodology section of PC and PVC sheets, since the PVC 90 second sheets were the first ones to be thermoformed, the data study has started as well with those sheets, as follows. Following, it can be seen both the PVC data example for 90s. While all the data will be analyzed, only one datasheet will be shown following, since the other ones can be found in *Annex V – Data comparison excel*.

Data comparison - PVC120 sheets + DIE 3

	(x)	Reason
Point 1	42	Left-side
Point 2	57	Around the middle of the top
Point 3	77	Right-side

Point 1

	Original (x)	Standardised (x)	Height (z)
PVC120s1	104,40893	41,90893	44,61784
PVC120s2	104,0005	41,5005	40,16003
PVC120s3	104,04026	41,54026	44,01129
DIE 3 - Before	104,94184	42,44184	42,53352
DIE 3 - After	105,19691	42,69691	41,72106
DIE 3 - SolidWorks	47	42	43

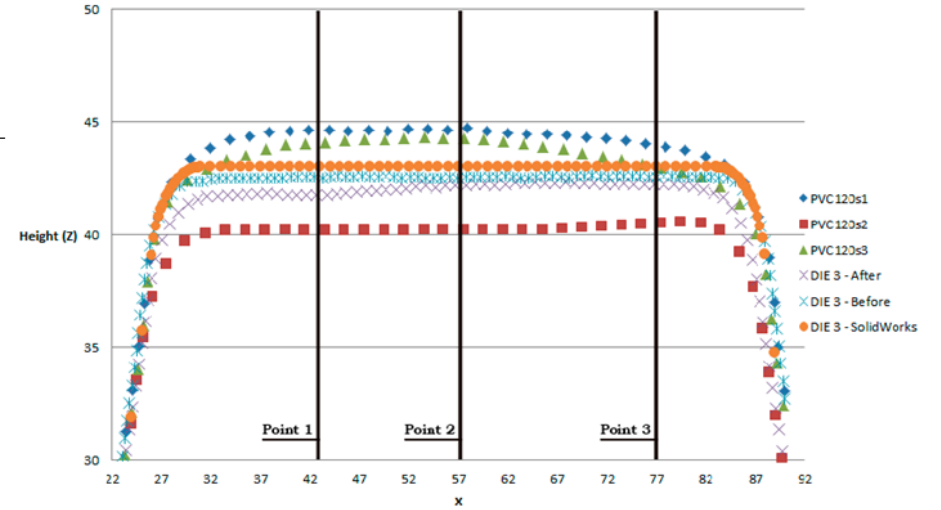
	PVC120s1	PVC120s2	PVC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC120s1		4,45781	0,60655	2,08432	2,89678	1,61784
PVC120s2	-4,45781		-3,85126	-2,37349	-1,56103	-2,83997
PVC120s3	-0,60655	3,85126		1,47777	2,29023	1,01129
DIE 3 - Before	-2,08432	2,37349	-1,47777		0,81246	-0,46648
DIE 3 - After	-2,89678	1,56103	-2,29023	-0,81246		-1,27894
DIE 3 - SolidWorks	-1,61784	2,83997	-1,01129	0,46648	1,27894	

Point 2

	Original (x)	Standardised (x)	Height (z)
PVC120s1	120,42132	57,92132	44,70044
PVC120s2	120,01039	57,51039	40,20652
PVC120s3	120,04234	57,54234	44,26018
DIE 3 - Before	119,4074	56,9074	42,5073
DIE 3 - After	120,21615	57,71615	42,18842
DIE 3 - SolidWorks	62	57	43

	PVC120s1	PVC120s2	PVC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC120s1		4,49392	0,44026	2,19314	2,51202	1,70044
PVC120s2	-4,49392		-4,05366	-2,30078	-1,9819	-2,79348
PVC120s3	-0,44026	4,05366		1,75288	2,07176	1,26018
DIE 3 - Before	-2,19314	2,30078	-1,75288		0,31888	-0,4927
DIE 3 - After	-2,51202	1,9819	-2,07176	-0,31888		-0,81158
DIE 3 - SolidWorks	-1,70044	2,79348	-1,26018	0,4927	0,81158	

PVC 120S 1,2 and 3 and 3<sup>rd</sup> DIE (before and after forming)



Point 3

	Original (x)	Standardised (x)	Height (z)
PVC120s1	140,43517	77,93517	43,85738
PVC120s2	140,00362	77,50362	40,49429
PVC120s3	140,0275	77,5275	42,97325
DIE 3 - Before	140,2766	77,7766	42,58749
DIE 3 - After	140,26958	77,76958	42,2092
DIE 3 - SolidWorks	82	77	43

	PVC120s1	PVC120s2	PVC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC120s1		3,36309	0,88413	1,26989	1,64818	0,85738
PVC120s2	-3,36309		-2,47896	-2,0932	-1,71491	-2,50571
PVC120s3	-0,88413	2,47896		0,38576	0,76405	-0,02675
DIE 3 - Before	-1,26989	2,0932	-0,38576		0,37829	-0,41251
DIE 3 - After	-1,64818	1,71491	-0,76405	-0,37829		-0,7908
DIE 3 - SolidWorks	-0,85738	2,50571	0,02675	0,41251	0,7908	

Illustration 24.- PVC120S + DIE3 comparison

With regards to the study of each and every PVC sheet, it will be started with the PVC sheets which the data has just been provided, PVC120s.

Firstly, it is important to state that each data sheet comparison does take into account the different DIE3 states as well as the PVC sheets for the same amount of seconds under thermal stress. Therefore, for PVC120seconds it can be seen three different points taken into account which data is compared relatively to every other PVC sheet and DIE3 state, in order to compare it correctly. Besides, the maximum height difference is also detailed as well as the smallest height difference, as the diagram in illustration 15 provides.

Given that information, PVC120 seconds can be seen as how every sheet does have a totally different form.

While PVC120S2 does have a lower height with regards to the DIE3, both PVC120S1 and S3 do have rounded topside.

The explanation for these cases is that PVC120S2 does have a height difference at the bottom side of the DIE3, and has not experienced a total deformation. Therefore, the PVC120S2 has not been able to adopt the needed height at the bottom and once the PVC sheet is placed to the CMM machine for data extracting its height is lower than expected. Nonetheless, PVC120S2 has been able to have topside which does match to the DIE3 silhouette, despite the height difference found, *Table 11*.

For both PVC120S1 and PVC120S3, it can be seen how even though the PVC sheet has been able to adopt the needed shape of the DIE3 with regards to its height, it has been unable to adopt the correct topside flat surface. That deformation could be due to a malfunction of the vacuum during the process of thermoforming or either because of an internal air bubble created during the process.

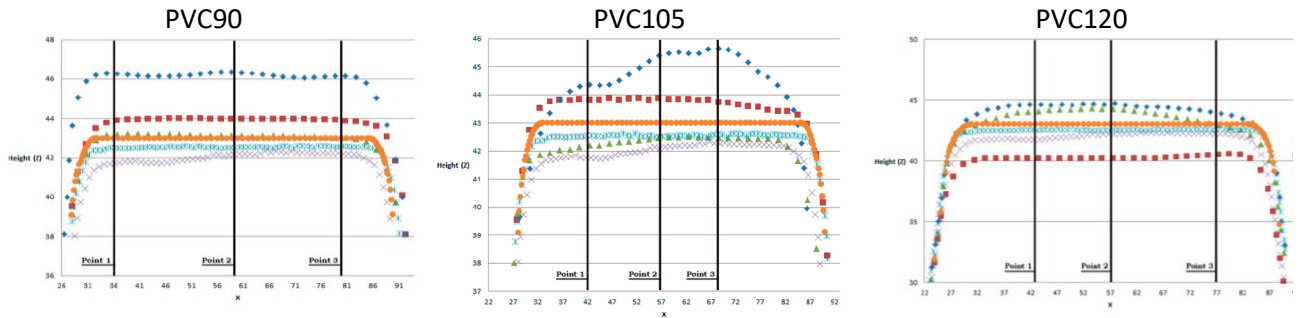
Regardless of the PVC sheets comparison, their height differences and problems with the adaptation of the DIE3 shape, it has to be stated that this projects object of study is to find a methodology to correctly compare those bodies and be able to extract this kind of information from it. Therefore, this objective has correctly been completed with the methodology adopted.

Together with the information already established with regards to PVC120, the explanation applies also to the other PVC 90 and 105 sheets. Besides, in *Table 10* it can be seen that both S1 and S2 for PVC90 and PVC105 do present an abnormal form, which is due to the defects seen in *PVC Sheets defects patterns*, such as *Illustration 22*.

A) *PVC\_105\_S2. Topside bump*; B) *PVC\_105\_S3. Height gap at baseline.* , which affects dimensionally as a higher gap at the topside of the sheets.

Therefore, it can be seen that a bump may be led by a height difference at the bottom, which could be due to a bad vacuum procedure. Therefore, those sheets do not follow a correct form given that they do not end up getting the right form, having a final semi-spherical profile. PVC\_120\_S2 is an example.

Table 10. PVC sheets comparison resumé



Mean	1.6884	1.3395	1.7405
E (%)	5.8034%	4.6042%	5.9826%

Table 11. PVC120 dimensional accuracy, mean values.

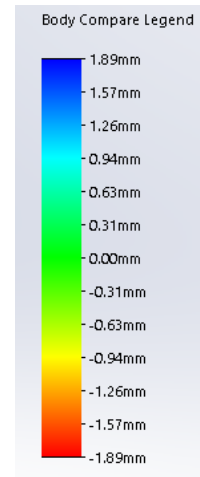
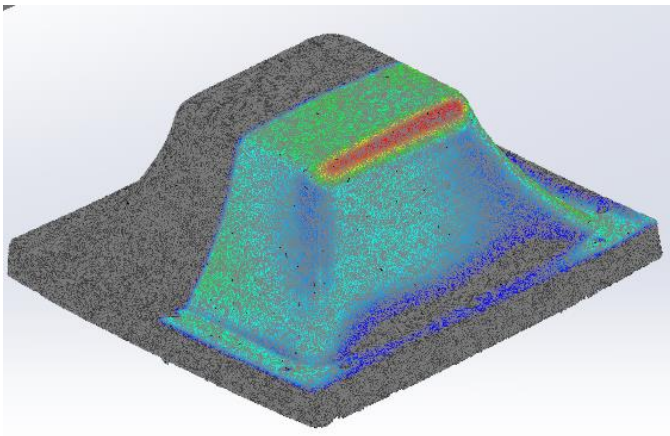
Values in mm (%deviation)	PVC120S1	PVC120S2	PVC120S3	DIE 3 – Before	DIE 3 – After	DIE 3 – Solid Works
PVC120S1	-	4.1049	0.6436	1.8491	2.3523	1.3918
PVC120S2	-4.1049	-	-3.4612	-2.2558	-1.7526	-2.7130
PVC120S3	-0.6436	3.4612	-	1.2054	1.7086	0.7482
DIE 3 – Before	-1.8491	2.2558	-1.2054	-	0.5032	-0.4572
DIE 3 – After	-2.3526	1.7526	-1.7086	-0.5032	-	-0.9604
DIE 3 – Solid Works	-1.3918	2.7130	-0.7482	0.4572	0.9604	-
Mean value	1.7405					
Total error percentage	5.9826%					

### 4.2.3. 3D scan comparison: DIE3-PVC Sheets

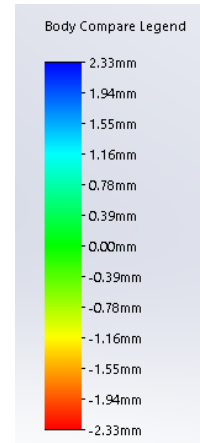
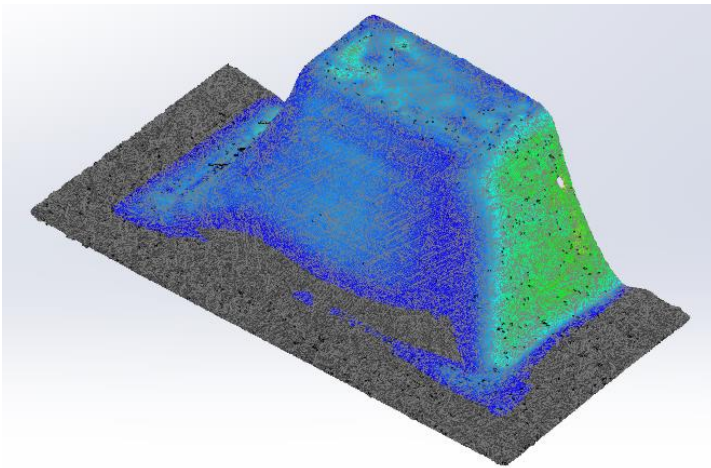
The comparison has been performed between both DIE3 design state and DIE3 scanned body for the first PVC sheet studied, while later on, only the comparison between DIE3 Scanned body and PVC sheet scan has been performed. In the following illustrations, *Illustration 25*, *Illustration 26*, *Illustration 27*, the dimensional difference is shown, in the following cases:

- Internal zone: It compares the DIE3 face with regards to the internal face of the PVC sheet.
- External zone: It compares the DIE3 face with regards to the external face of the PVC sheet.

**PVC90S3**



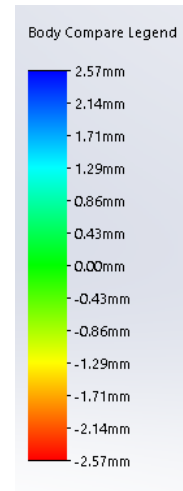
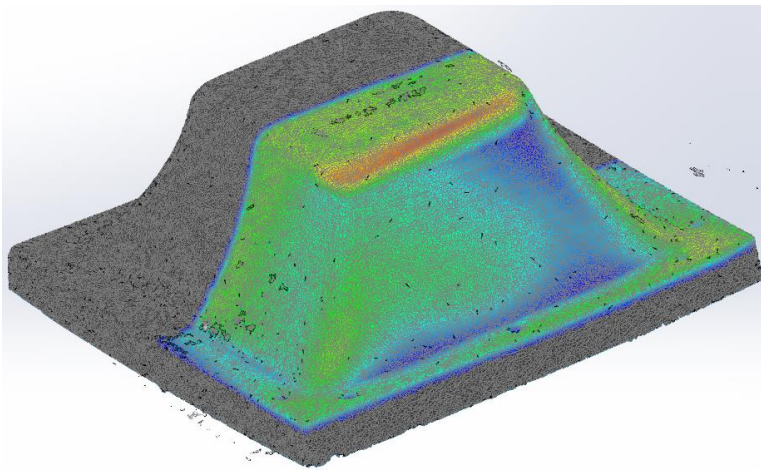
A)



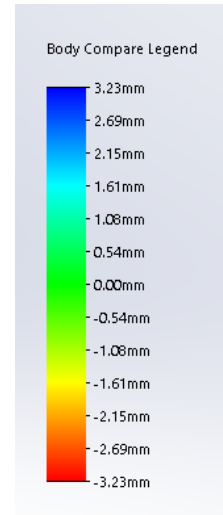
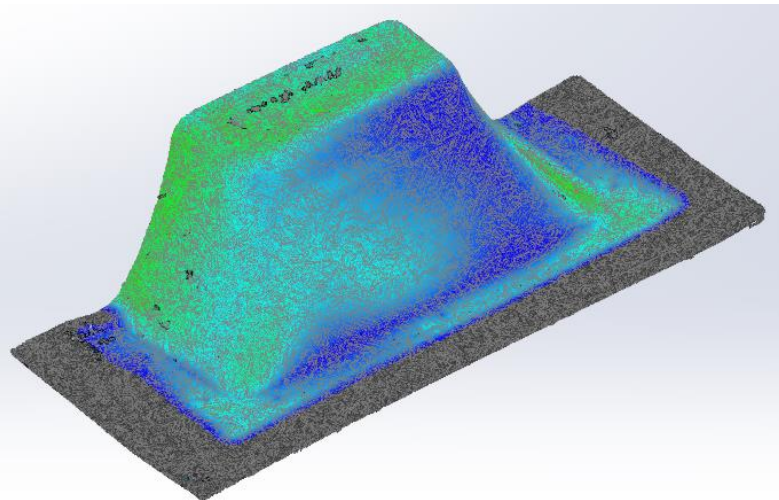
B)

*Illustration 25. PVC90S3 double scan comparison. A) Internal zone; B) External zone.*

**PVC 105S1**



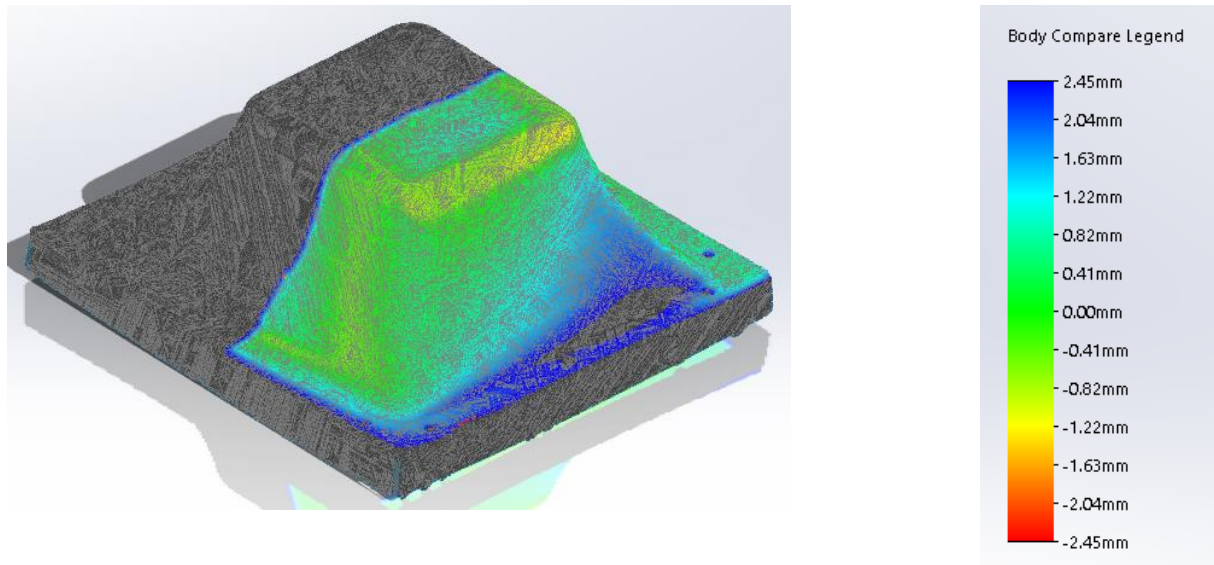
A)



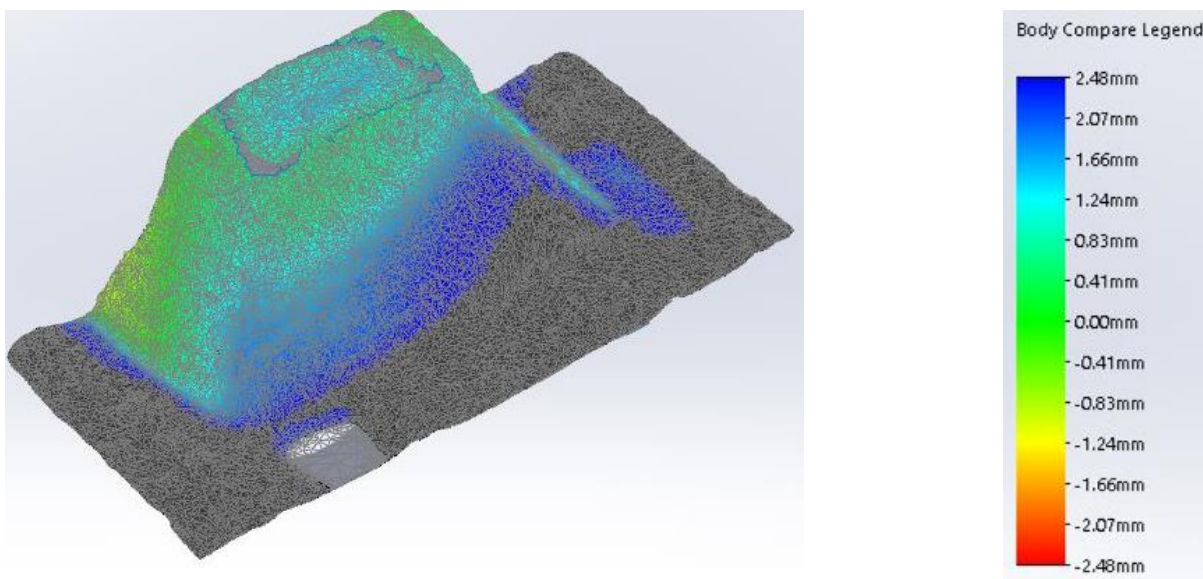
B)

Illustration 26. PVC105S1 double scan comparison. A) Internal zone; B) External zone.

### PVC120S3



A)



B)

Illustration 27. PVC120S3 double scan comparison. A) Internal zone; B) External zone

Therefore, the aim of this dual zone analysis is to extract the height difference between the PVC face in contact with the DIE3 and, as well, have an idea of how it translates with regard to the external and untouched face of the PVC sheet.

As it should be, it can be extracted that the height difference in the external zone is higher, and it could be extrapolated that the height difference between the internal zone and external zone in one point does refer to the PVC sheet thickness after being thermoformed.



*Table 12. PVC Solidworks – Dimensional accuracy*

<i>Values in mm</i>	<b>PVC90S3</b>	<b>PVC105S1</b>	<b>PVC120S3</b>
<b>Internal face</b>	0.94	0.86	0.82
<b>Error percentage</b>	3.23%	2.96%	2.82%

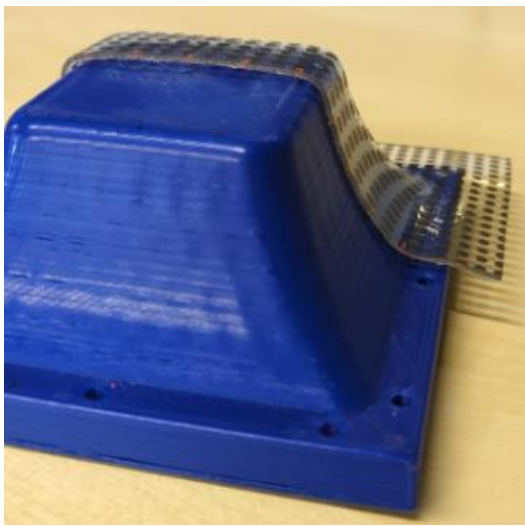
The external face error is not calculated since it would not be right to perform it with the actual data. Taking *Illustration 25* as example, it should be a 2.3mm external face accuracy which would translate to an 8.01% of error but actually, the dimensional difference between the external face of the PVC and the DIE 3, does take into account both the dimensional difference between the DIE 3 with regards to the Internal zone, which is detailed in *Table 12*, and also the sheet thickness, and therefore the value provided by the Solidworks is useful to see that the dimensional difference pattern with regards to the DIE 3 remains similar but unfortunately it is not useful to compare dimensions.

### 4.3. PC Sheets data analysis

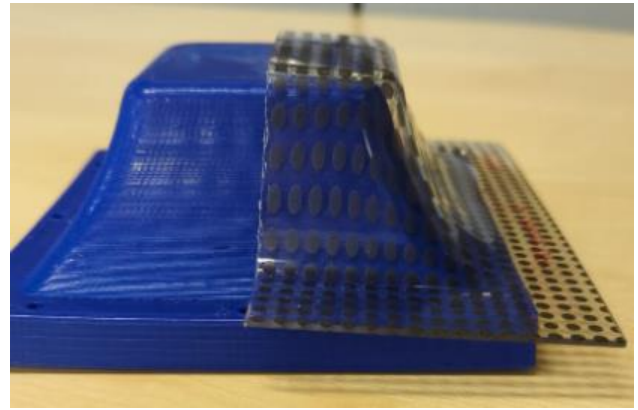
This section presents the different data treatment followed for the dimensional study for the different PC sheets. As well as what happened with the DIE3, it comprehends both the CMM Machine and 3D Scan usage.

#### 4.3.1. PC Sheets defects patterns

Starting with 90 seconds PC sheets, the same pattern does occur while thermoforming, which will be present in 90 seconds, 105 and 120 PC sheets. There is always a top side bump and, as well, a height difference at the baseline, . Besides, an increasing formation of bubbles has been found on the thermoplastic sheet as time under the heater increased.



A)



B)

Illustration 28. PC\_90\_S1 defects. A) Bottom height difference & Bump topside; B) Lateral unmatching the shape.

Additionally, following it is shown a résumé table of the defects patterns found in PVC sheets, which do go hand by hand with the data.

Table 13.- PC defect patterns.

SHEET	DISPLACEMENT OF LAYERS	BUMPS	BUBBLES	HEIGHT DIFFERENCE AT THE BOTTOM / BASE	WRINKLES / FOLDING
PC 90S1	-	X	-	X	-
PC 90S2	-	X	-	X	-
PC 90S3	-	X	-	X	-

SHEET	DISPLACEMENT OF LAYERS	BUMPS	BUBBLES	HEIGHT DIFFERENCE AT THE BOTTOM / BASE	WRINKLES / FOLDING
PC 105 S2	-	X	X	X	-
PC 105 S3	-	X	X	X	-
PC 120 S1	-	X	XX	X	-
PC 120 S2	-	X	XX	X	-
PC 120 S3	-	X	XX	X	-

As it has been just shown with PC and PVC defects illustrations, there are common physical deformations and similar problems encountered in the thermoformed sheets. Following, they are listed and explained in the table, with their possible causes as well.

Table 14.- Thermoplastic sheets possible defects.

Defect	Definition	Causes
Bubbles	Voids on the inner plastic layer	<ol style="list-style-type: none"> <li>1) Absorbed moisture by the plastics' inner layer</li> <li>2) Plastic sheet temperature may be too high</li> <li>3) Plastic sheet temperature may not be uniform</li> </ol>
Unwanted folds, webbing or wrinkles	The plastic folds into itself. During vacuum molding process, the thermoplastic stretches in a way that wasn't planned	<ol style="list-style-type: none"> <li>1) Plastic sheet temperature may be too high, causing premature melting or causing the plastic to stick around the cavity</li> <li>2) Mold parts are too close together</li> <li>3) Insufficient vacuum</li> </ol>
Dimensional inconsistencies	The thermoformed sheet does not meet the required dimensions.	<ol style="list-style-type: none"> <li>1) Inadequate vacuum or air pressure applied.</li> <li>2) Improper forming method used for a specific application or material.</li> </ol>
Defect	Definition	Causes
Warpage	Deformed shape of the overall thermoplastic sheet.	<ol style="list-style-type: none"> <li>1) Parts are cooled unevenly</li> <li>2) Mold temperature tool is not uniform</li> </ol>

For both PC and PVC, the different types of common defects which can be found after thermoforming due to different causes: heat, shape building and deformation or just material stress. Possible corrective actions which could be taken in further thermoforming processes, which should be studied, are the following:

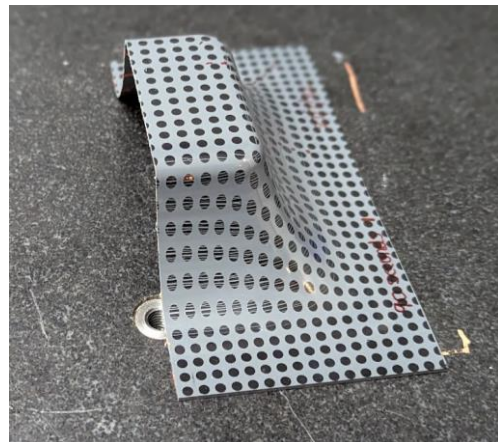
- Lowering the forming temperature: it may lead to less bubble formation and avoiding unwanted folds or wrinkles. It has been seen that the last thermoformed sheets, PC105 and PC120, are the ones with the most bubbles. Therefore, lowering the temperature after a few thermoformed sheets or stopping the process in order to avoid a possible overheating may be the correct action to perform.
- Improper vacuum functionality: unwanted folds, thickness inconsistency and warpage are the main defects which could be avoided by it. As well, the bottom height difference found at the base in both PC and PVC may be due to a bad vacuum procedure.

### 4.3.2. PC Sheets data comparison

The process for taking out the data for the PC sheets with the CMM machine has been the same as with the DIE3, following, an example with a PVC sheet, *Illustration 29*.



A)



B)

*Illustration 29. A) CMM machine working on a PVC thermoformed sheet; B) PVC sheet cut*

As stated in the methodology section of PC and PVC sheets, since the PVC 90 second sheets were the first ones to be thermoformed, the data study has started as well with those sheets, as follows. When it comes down to the data comparison, via excel. Following, it can be seen one example of PC data, *Illustration 30*. While all the data will be analyzed, only one datasheet will be shown following, since the other ones can be found in *Annex V – Data comparison excel*.

Data comparison - PC120 sheets + DIE 3

	(x)	Reason
Point 1	42	Left-side / Lowest
Point 2	56	Around the middle of the top
Point 3	75	Right-side

**Point 1**

	Original (x)	Standardised (x)	Height (z)
PC120s1	100,22589	43,12589	42,44733
PC120s2	42,74348	42,39619	42,74348
PC120s3	102,02536	42,92536	43,23922
DIE 3 - Before	98,08896	42,48896	42,56264
DIE 3 - After	42,89705	42,89705	41,74738
DIE 3 - SolidWorks	48	42	43

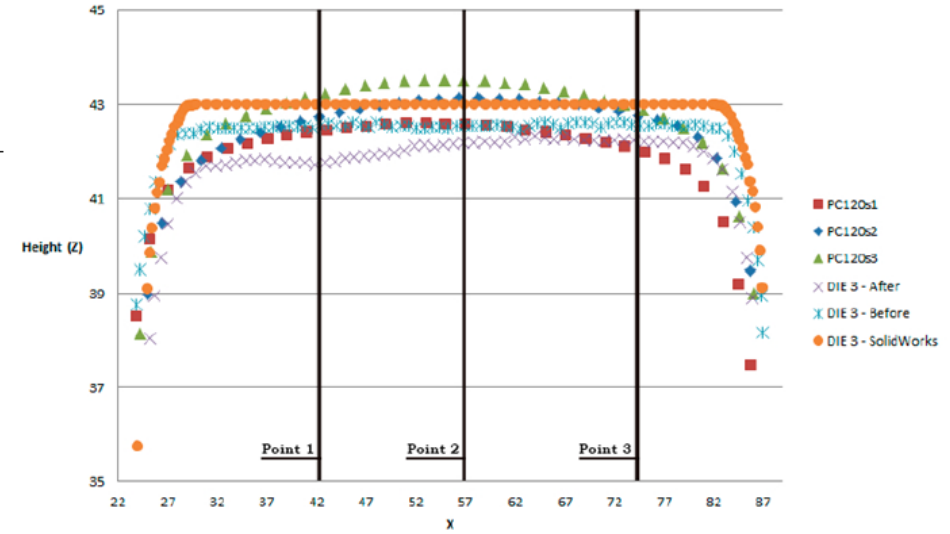
	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC120s1		-0,29615	-0,79189	-0,11531	0,69995	-0,55267
PC120s2	0,29615		-0,49574	0,18084	0,9961	-0,25652
PC120s3	0,79189	0,49574		0,67658	1,49184	0,23922
DIE 3 - Before	0,11531	-0,18084	-0,67658		0,81526	-0,43736
DIE 3 - After	-0,69995	-0,9961	-1,49184	-0,81526		-1,25262
DIE 3 - SolidWorks	0,55267	0,25652	-0,23922	0,43736	1,25262	

**Point 2**

	Original (x)	Standardised (x)	Height (z)
PC120s1	114,2259	57,1259	42,57239
PC120s2	43,13043	56,3927	43,13043
PC120s3	116,02247	56,92247	43,51226
DIE 3 - Before	111,75167	56,15167	42,53591
DIE 3 - After	56,91155	56,91155	42,18842
DIE 3 - SolidWorks	62	56	43

	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC120s1		-0,55804	-0,93987	0,03648	0,38397	-0,42761
PC120s2	0,55804		-0,38183	0,59452	0,94201	0,13043
PC120s3	0,93987	0,38183		0,97635	1,32384	0,51226
DIE 3 - Before	-0,03648	-0,59452	-0,97635		0,34749	-0,46409
DIE 3 - After	-0,38397	-0,94201	-1,32384	-0,34749		-0,81158
DIE 3 - SolidWorks	0,42761	-0,13043	-0,51226	0,46409	0,81158	

PC 120S + DIE 3



**Point 3**

	Original (x)	Standardised (x)	Height (z)
PC120s1	132,23708	75,13708	41,97238
PC120s2	42,66764	76,39585	42,66764
PC120s3	134,02915	74,92915	42,86445
DIE 3 - Before	131,01169	75,41169	42,54947
DIE 3 - After	75,96335	75,96335	42,21908
DIE 3 - SolidWorks	81	75	43

	PC120s1	PC120s2	PC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC120s1		-0,69526	-0,89207	-0,57709	-0,2467	-1,02762
PC120s2	0,69526		-0,19681	0,11817	0,44856	-0,33236
PC120s3	0,89207	0,19681		0,31498	0,64537	-0,13555
DIE 3 - Before	0,57709	-0,11817	-0,31498		0,33039	-0,45053
DIE 3 - After	0,2467	-0,44856	-0,64537	-0,33039		-0,78092
DIE 3 - SolidWorks	1,02762	0,33236	0,13555	0,45053	0,78092	

Illustration 30. PC120S + DIE3 comparison

With regards to the study of each and every PC sheet, it will be started with the PVC sheets which the data has just been provided, PC120s.

Following the explanations already given in *PVC Sheets data comparison*, the comparison for PC120S is fairly similar.

On one hand, the defects which appeared in all three sheets are visible given the shape of their topside with regards to DIE 3 – Solidworks.

Also, it is important to notice that even though there is a slightly higher topside height difference in the central zone with regards to the laterals; all sheets have preserved and followed a similar deformation.

Since with the last comparison for PVC there was a sheet which looked like a real liability to the data, in this case it is expected and, in

*Table 16. PC120 dimensional accuracy, mean values.* it can be seen how the dimensional accuracy is so much accurate with regards to the last comparison done.

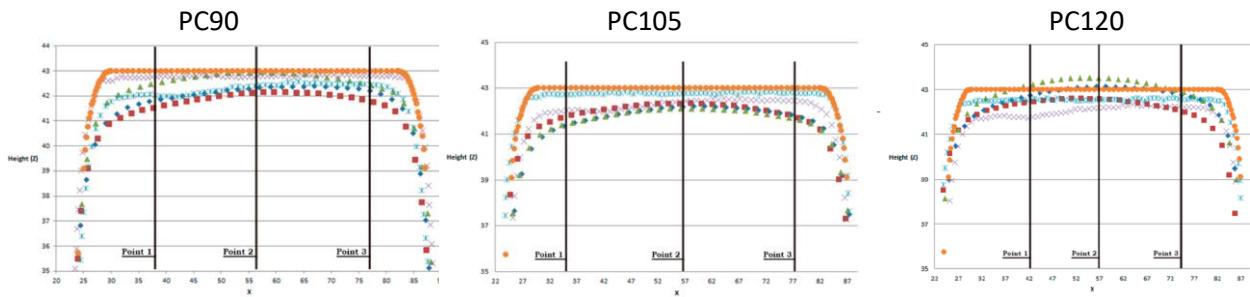
Therefore, it is safe to see the data as fairly compact and, as well, reliable for taking the accuracy process as a procedure for comparing different profiles.

After all, it is also visible how PC120 S1 may have suffered a spring-back effect, probably due to bad vacuum operation during the thermoforming process.

Together with the information already established with regards to PC120, the explanation applies also to the other PC 90 and 105 sheets, *Table 15.* Besides, in it can be seen that the spring-back effect is noticeable in all cases for PC sheets, which may be not only due to a bad vacuum but also may be due to the examination of the PC sheets after being cut or also due to uneven cooling afterwards.

Therefore, those sheets do not follow a correct form given that they do not end up getting the right form, having a final semi-spherical profile.

*Table 15. PC sheets comparison resumé*



Mean	0.5580	0.6444	0.5382
E (%)	1.9179%	2.2149%	1.8499%

Table 16. PC120 dimensional accuracy, mean values.

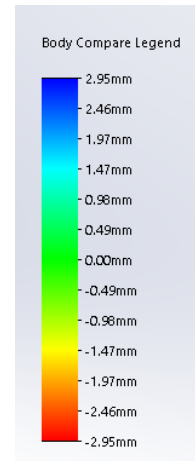
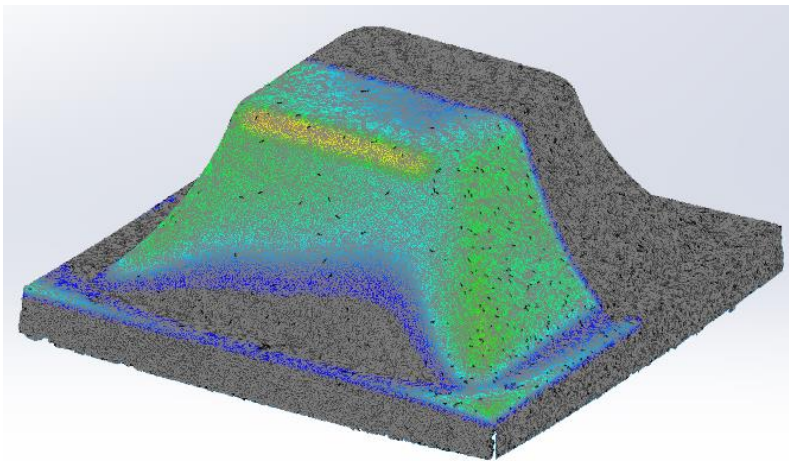
<i>Values in mm (%deviation)</i>	<b>PC120S1</b>	<b>PC120S2</b>	<b>PC120S3</b>	<b>DIE 3 – Before</b>	<b>DIE 3 – After</b>	<b>DIE 3 – Solid Works</b>
<b>PC120S1</b>	-	-0,516483333	-0,87461	-0,21864	0,279073	-0,6693
<b>PC120S2</b>	0,516483333	-	-0,358126667	0,297843333	0,795557	-0,152816667
<b>PC120S3</b>	0,87461	0,358126667	-	0,65597	1,153683	0,20531
<b>DIE 3 – Before</b>	0,21864	-0,297843333	-0,65597	-	0,497713	-0,45066
<b>DIE 3 – After</b>	-0,279073333	-0,795556667	-1,153683333	-0,497713333	-	-0,948373333
<b>DIE 3 – Solid Works</b>	0,6693	0,152816667	-0,20531	0,45066	0,948373	-
<b>Mean value</b>	0.5382					
<b>Total error percentage</b>	1.8499%					



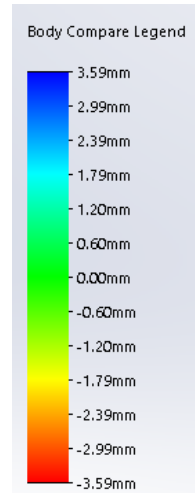
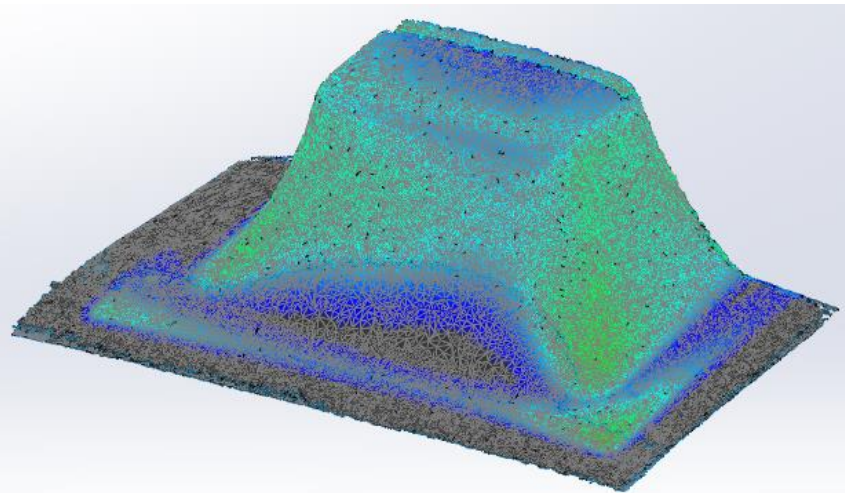
### 4.3.3. 3D scan comparison: DIE3-PC Sheets

Following the same procedure as in *3D scan comparison: DIE3-PVC Sheets*, the comparison has been performed between both DIE3 design state and DIE3 scanned body for the first PVC sheet studied, while later on, only the comparison between DIE3 Scanned body and PVC sheet scan has been performed. In the following illustrations, *Illustration 31, Illustration 32, Illustration 33*, the dimensional difference is shown, in the following cases:

#### PC90S3



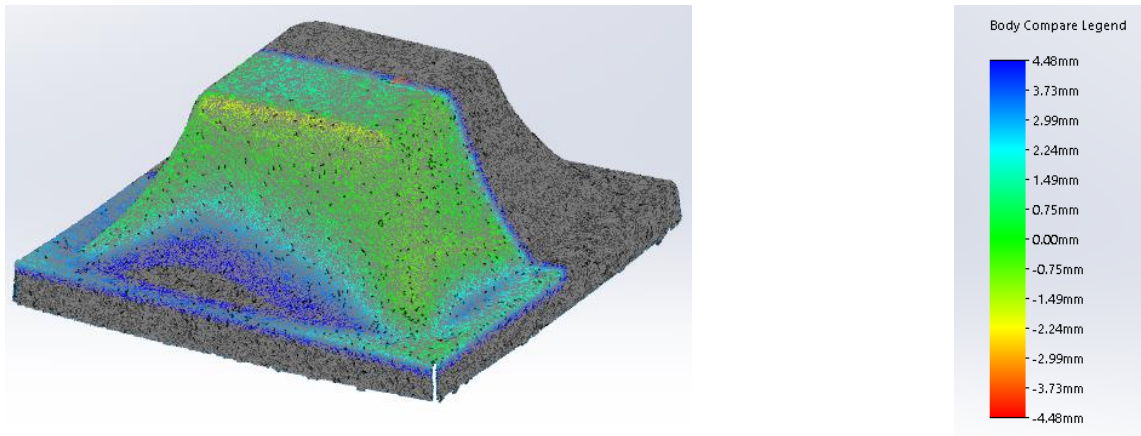
A)



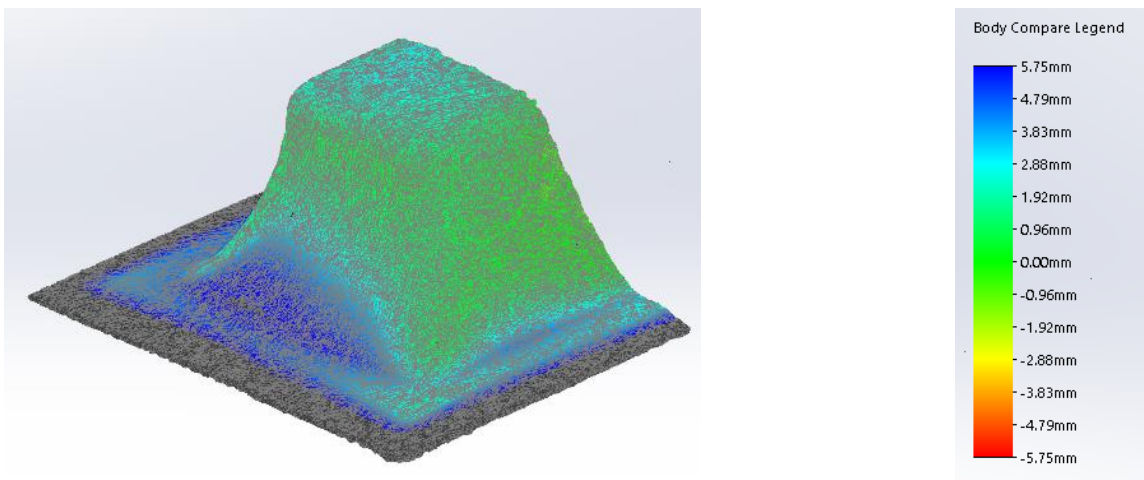
B)

*Illustration 31. PC90S3 double scan comparison. A) Internal zone; B) External zone.*

**PC105S1**



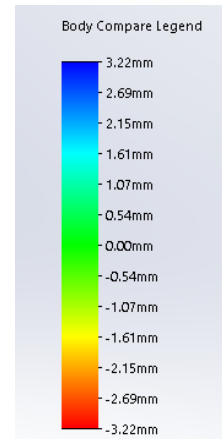
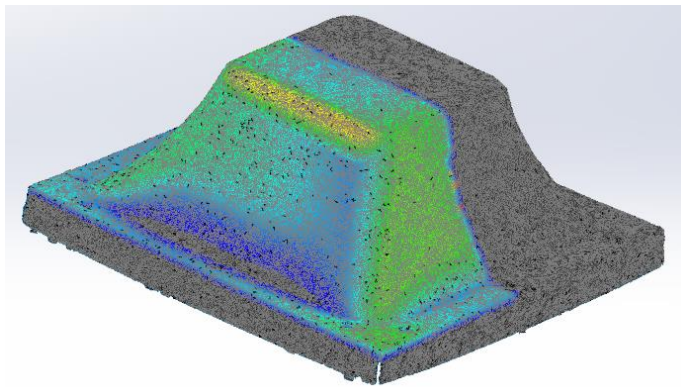
A)



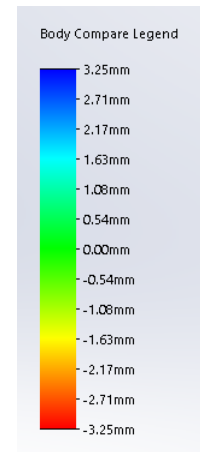
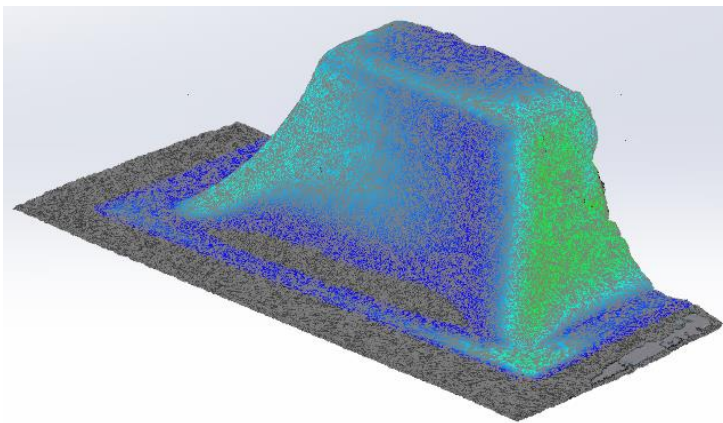
B)

*Illustration 32. PC105S1 double scan comparison. A) Internal zone; B) External zone.*

**PC120S1**



A)



B)

Illustration 33. PC120S3 double scan comparison. A) Internal zone; B) External zone.

As well as how it happened with the PVC comparison sheets, the same explanation can be imported to the PC sheets, *Table 17*.

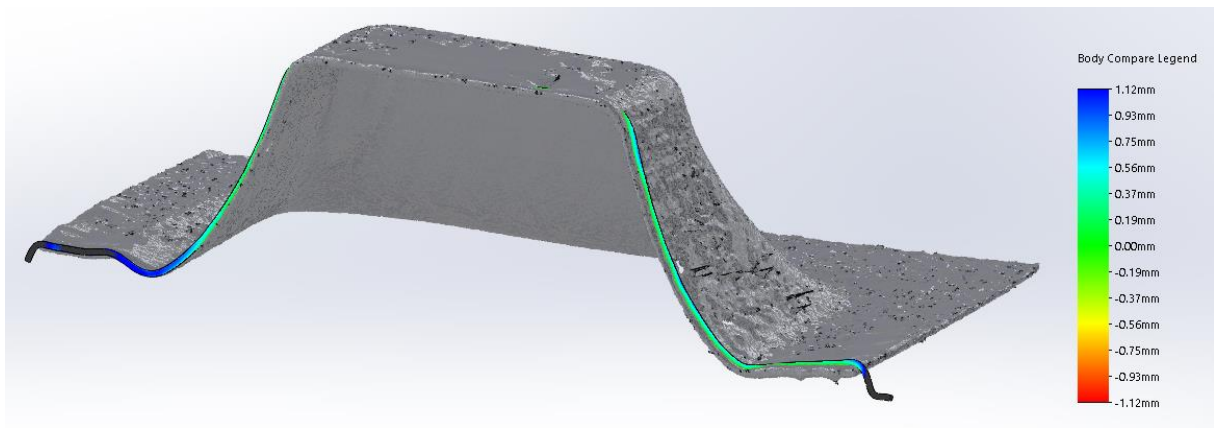
*Table 17. PVC Solidworks – Dimensional accuracy*

Values in mm	PC90S3	PC105S1	PC120S3
Internal face	1.97	2.24	1.61
Error percentage	6.77%	7.69%	5.53%

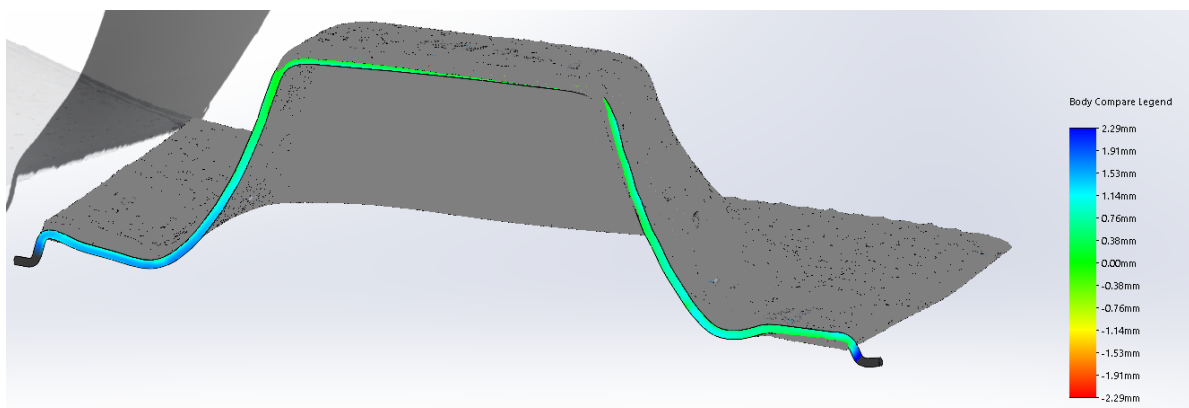
#### 4.4. General comparison: 3D scanned data vs. CMM profiles

After having studied and analyzed PVC and PC sheets with data taken differently, it has been performed a general comparison between the 3D scanned data and the CMM profiles in Solidworks, so that the same data obtained differently can be analyzed. While PVC comparison is represented by *Illustration 34*, *Illustration 35* and *Illustration 36*, PC comparison is represented by *Illustration 37*, *Illustration 38* and *Illustration 39*, while *Table 18* works as a data accuracy summary.

The CMM profiles, which were saved as .txt files, have been transformed to 3D thin 1mm revolved bodies in Solidworks and have been compared with their body. Following, the results obtained in PVC sheets.



*Illustration 34. PVC90S3 3D scan vs. CMM data comparison. Height difference.*



*Illustration 35. PVC105S3 3D scan vs. CMM data comparison. Height difference.*

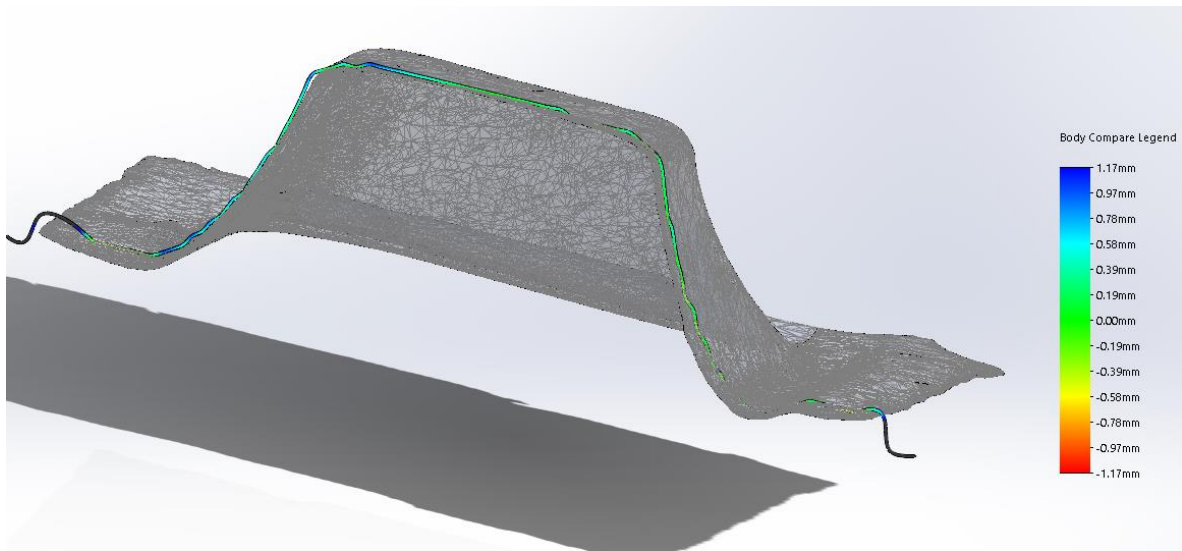


Illustration 36. PVC120S3 3D scan vs. CMM data comparison. Height difference.

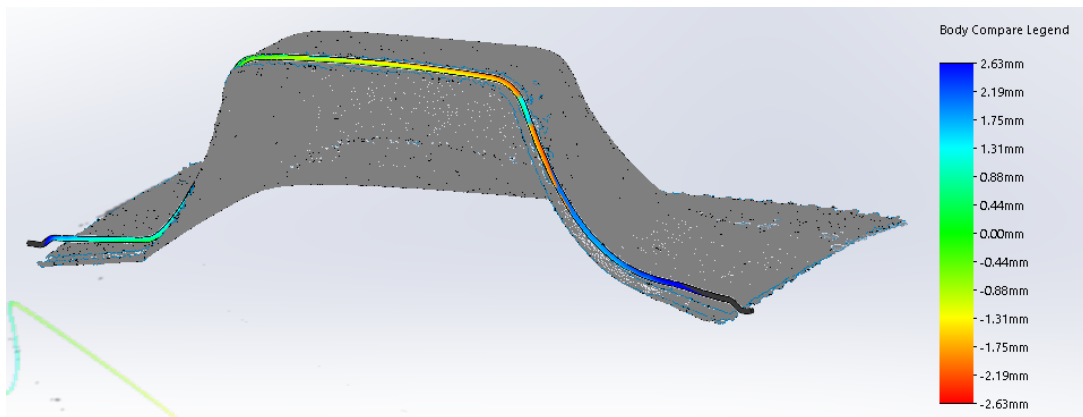


Illustration 37. PC90S3 3D scan vs. CMM data comparison. Height difference.

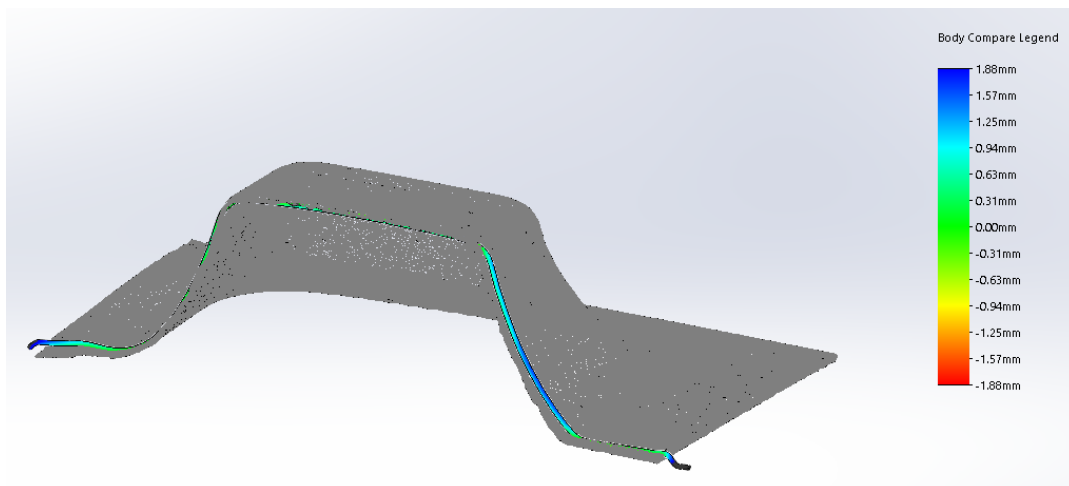


Illustration 38. PC105S1 3D scan vs. CMM data comparison. Height difference.

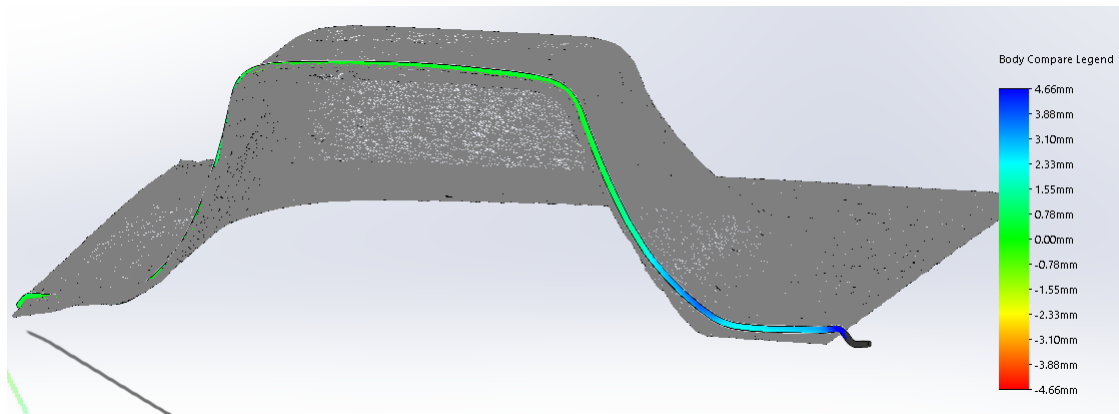


Illustration 39. PC120S3 3D scan vs. CMM data comparison. Height difference.

It can be seen that in all three comparison that both the CMM profiles and the body silhouette do follow a similar pattern all along the surface. Nonetheless, it can also be seen that the height difference between them varies substantially between different bodies and, while for PVC120S3 most of the CMM profile does stay between the ranges of  $\pm 0.39\text{mm}$ , for PVC105S3, the sides go up to  $+1.14\text{mm}$ .

Theoretically, the body comparison should give a  $0.00\text{mm}$  of difference, since it has been tried to place the CMM profile to the exact same place of the 3D Scanned body so that it matches. It could, actually, be accepted a  $0.01\text{mm}$  of difference since the CMM machine does have a  $0.01\text{mm}$  tolerance and the 3D Scan does assure a  $0.02\text{mm}$  of tolerance, but it can be seen that it is not the case.

Therefore, in order to understand the body comparison of CMM Machine with regards to the 3D Scanned body, it should be taken into account the methodology to place the CMM data into Solidworks for correct comparison.

While the 3D Scanned body is created directly and the surface is placed into Solidworks, the CMM profile does have to go through a process of data standardization to apply the CMM data to Solidworks and then create a body with this data profile. The difficulty lies on the creation of the body once the profile has been implemented into Solidworks. Since the CMM profile is a 3D Sketch for the software, a body has to be created, and while the PVC sheet is  $1.5\text{mm}$  thick, it is not possible to create a  $1.5\text{mm}$  extrusion in one specific direction given that it is a 3D Sketch created from scratch without any references. Therefore, it is needed to create a tubular section, using the CMM profile as the path for it, with  $1.5\text{mm}$  of diameter, and then the body is created. Even though it is a quick and easy solution, which does give this process the capacity to compare both hardware's results, it does also give a problem for comparing both bodies, since now we have a tubular section that only the central point does actually have the right dimensions of the CMM section, giving then an extra  $1.5\text{mm}$  of tolerance at any point given.

Table 18. General comparison – Dimensional accuracy

Values in mm	PVC90S3	PVC105S1	PVC120S3
--------------	---------	----------	----------

<b>Body comparison</b>	0.56	1.14	0.58
<b>Error percentage</b>	1.92%	3.92%	1.99%
<i>Values in mm</i>	<b>PC90S3</b>	<b>PC105S1</b>	<b>PC120S3</b>
<b>Body comparison</b>	2.63	1.25	3.10
<b>Error percentage</b>	9.04%	4.29%	10.66%

## 5. Software limitations, problematic, key points and future research

Even though a well-treated and clear path has been created to treat scanned 3D data and the resources available have been optimized by the shape and size of the DIE and sheets treated, there have been limitations found and different problematic have been recurrently found while the software usage.

Scan software main difficulties/remarks:

- Body may remain unclosed. Even though the turning plate does give the easy to shape a 360° view of the scanned object, it also restricts the base of the body analyzed, which ultimately leads to another complementary scan and alignment measurements in order to close the body correctly, while is not possible to just close the body automatically by a plain surface. Besides, the software is only capable to close holes if they are smaller than 100mm.
- When exporting the document, it appears in a randomly position and coordinates. It may be useful to be able to determine a point (0, 0, 0) just before or after the scan so that, when the .STL file is imported, it can be easily compared and treated.
- The illustrations contained in *3D scan comparison: DIE3-PVC Sheets* and also in *3D scan comparison: DIE3-PC Sheets* , there appears a visual problem which has not allowed to generate the best comparison possible. Taking *Illustration 25. PVC90S3 double scan comparison. A) Internal zone; B) External zone.* as example, in the Internal Zone there is a surface which always appears in red, regardless of which PVC or PC sheet you are looking at. It is because one limitation of the Scan is that the internal zone of the PVC or PC sheet seems to be invisible for it, and creates a gap of the internal face of the sheet, creating a height difference. In this case, it has been solved by closing the gap, but the hole created does not follow the same direction of the body, and creates a surface which interferes with the DIE 3 body once it is in comparison, hereby the red color of it.

Geomagic remarks:

- Newer Geomagic versions do allow a 2D and 3D comparison process, which should be studied. In that case, it may be possible to compare a comparison between bodies and without the need of other software such as Solidworks. Besides, there is a newly added pricey plug-in in Solidworks which includes Geomagic. Both options could simplify comparison process and its steps to the final end, as well as allow extra comparison methods.

CAD software remarks (Solidworks, Solid Edge or Autodesk Fusion 360):



- In all cases, it has been found that there is a limit of facets/triangles established by CAD software to import 3D scanned bodies as mesh bodies, which are approximately 10000 facets. If the number of facets is largely outnumbered, the software is not able to create the body and it just opens as a surface, not allowing creating a coordinates system and comparing bodies.

The precedent explanation may not actually be a big of a problem but poses the following statement:

Since the scan allows us to have a +1 million facets in a body, shape and dimensional accuracy is being lost at simplify the mesh.

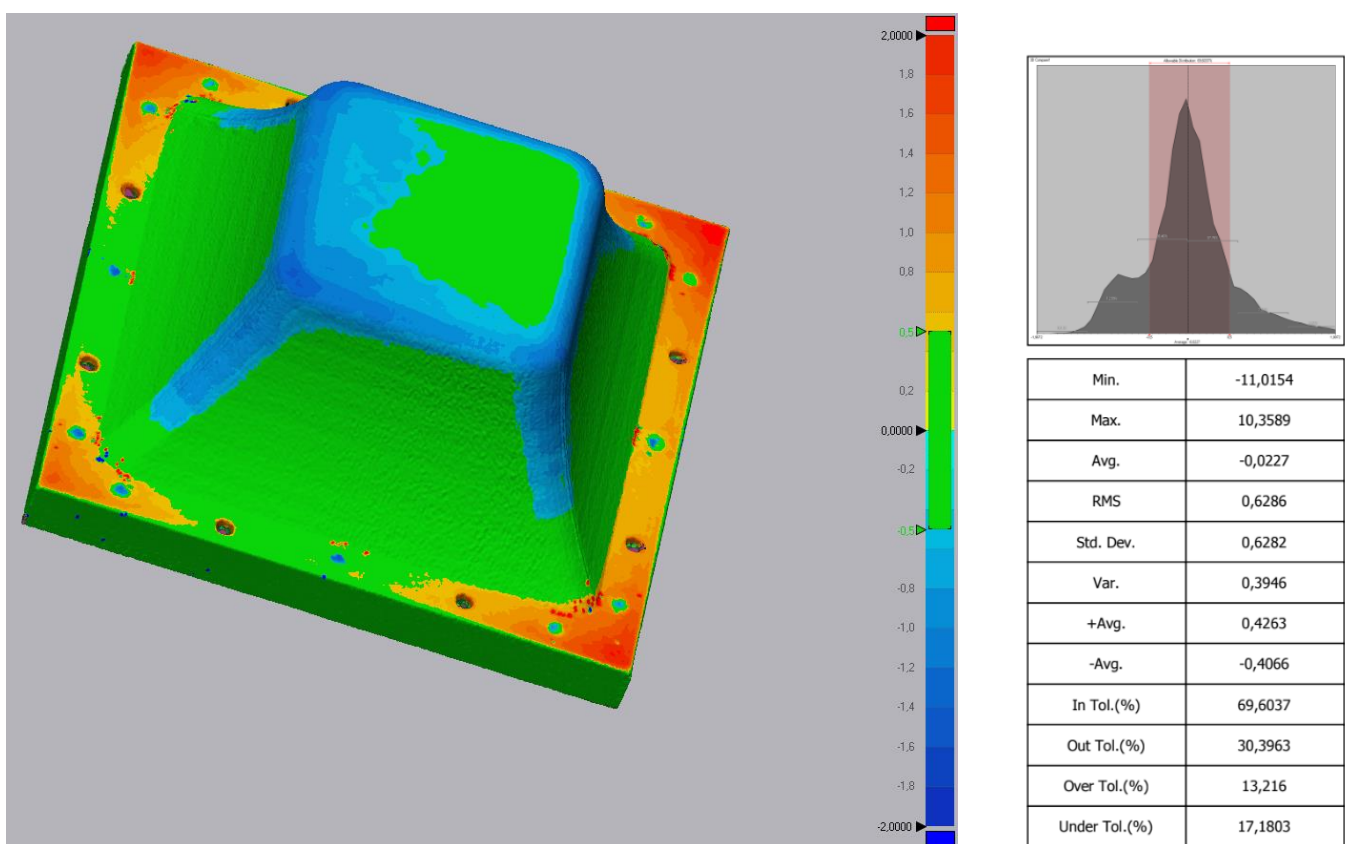
Software have been developing recently and adapting rapidly to mesh bodies since they are more common in the industry and, therefore, the number of facets allowed creating a defined mesh body will likely increase in the near future, optimizing the scan hardware usage.

Newer versions of the used software may include new functions which could facilitate the data treatment established and/or simplify it. Specifically, some functionality has already been found which could ultimately help the data treatment process, such as:

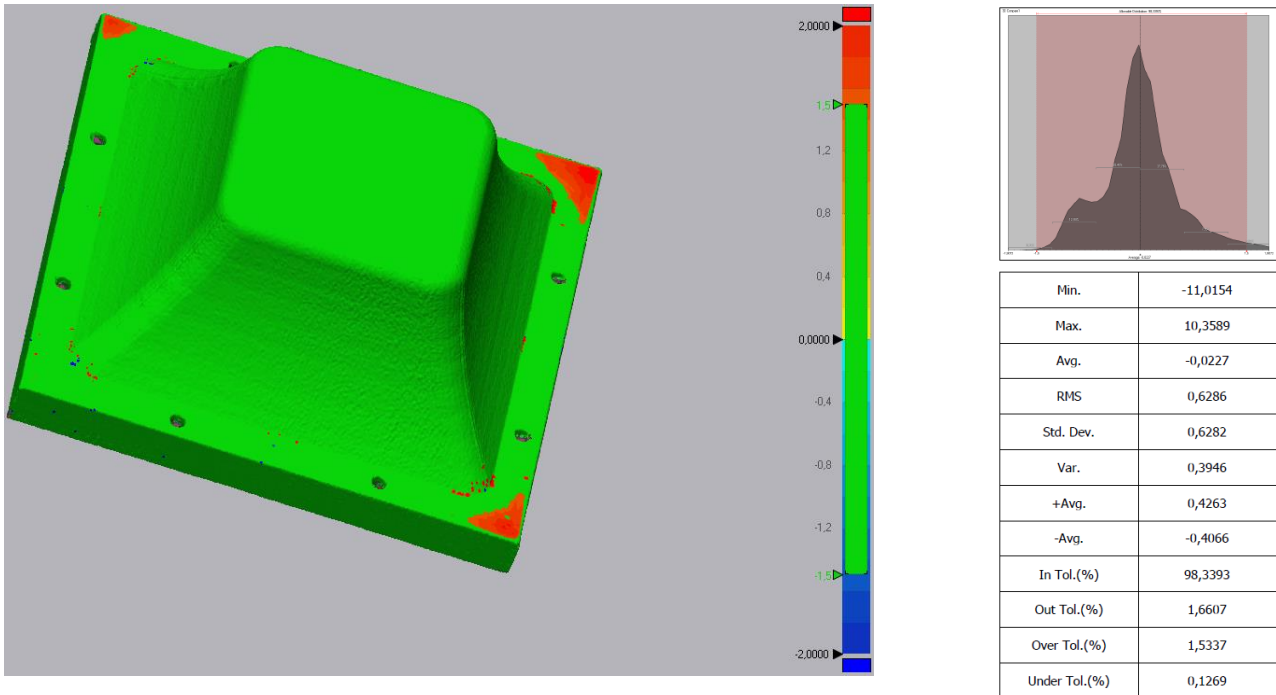
- 2023 Solidworks / Solid Edge or Autodesk Fusion 360 (may include more facets treatment).
- Solidworks new Geomagic plug-in, which should be studied.
- Geomagic Control X version does allow 2D and 3D comparison, which should be studied.

## 6. Data processing methodology validation

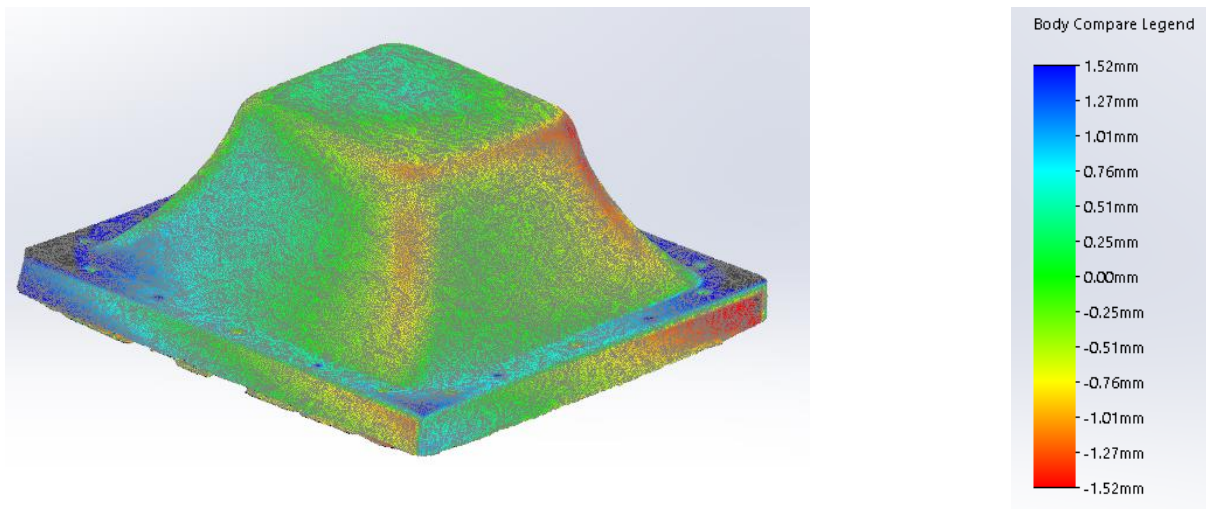
After performing the whole process for the different bodies, the examination of the software just explained in *Software limitations, problematic, key points and future research*<sup>68</sup> have been tried, and it has been able to get a 14-day trial for Geomagic Control X, which does perform automatically the positioning of similar bodies, and also provides the discrete data and data analysis which allows an excellent comparison. Therefore, since DIE 3 is the main body which has been examined in more detail, a comparison between DIE3 Before and DIE3 After has been performed and, given the information provided by Geomagic Control X, the tolerance of the thermoforming process can be analysed and compared with *Thermoforming process wear* results. Following, the comparative table between the results obtained with Solidworks and the data provided by using Geomagic Control X, *Illustration 40*:



A)



B)



C)

Illustration 40. Geomagic Control X vs. Solidworks comparison

The important take about *Illustration 20* is the following:

- Since for Solidworks has been established a  $\pm 1.52\text{mm}$  as a total accuracy of comparison while having most data around values  $\pm 0.51\text{mm}$ , for Geomagic Control X has been defined two different tolerances, the first one (A) with a tolerance of  $\pm 0.50\text{mm}$  while having (B) under a tolerance of  $\pm 1.50\text{mm}$ . Thus, comparing the

three images A, B and C, it can be seen that the process performed via Solidworks does match with the comparison automatically performed by Geomagic Control X, which provides a wide variety of data for the comparison.

Therefore, A) defines that 69.6% of data is found inside the range of  $\pm 0.50\text{mm}$  while B) defines a total of 98.34% of data found inside the range of  $\pm 1.50\text{mm}$ . Besides, it can also be seen that the average of the whole process defines a  $-0.0227\text{mm}$ . Unfortunately, the maximum and minimum difference, which is set to  $-11.0154$  and  $10.3589$  respectively, is probably due to a problematic with the scan, having a facet unmatched between both bodies and, therefore, giving the total height at that point as the maximum differential. Looking at the colour legend at both A), B) and even C), it can be seen that the maximum difference should be a bit higher than around  $2.00\text{mm}$ , and located at the extremes of the body, agreeing with the mold defect seen in *Table 5.- DIE3 after thermoforming defects*.

*Table 19. Thermoforming process wear dimensional accuracy*

<i>Values in mm</i>	<b>Geomagic Control X</b>	<b>SolidWorks Comparison</b>
<b>Maximum difference</b>	-	1.52
<b>Standard deviation / Mean value</b>	0.6282	0.76
<b>Error percentage</b>	2.1593%	2.6123%

## 7. Budget

In order to give a summary about the spending made throughout the present project, this section will take into account all the following costs, which represents the summary of the *Annex VIII – Budgeting*:

- Personal expenses
- Management expenses
- Administrative expenses
- Operating expenses (licenses)

The total price, sums up to **20.076,31 €** for the project.

## 8. Conclusions

The following conclusions are done with respect to the capabilities of study the dimensional tolerance and capacity to analyze and compare bodies, instead of focusing on the results of the thermoforming process to the bodies wear.

Therefore, there are two main points when it comes down to approach the capabilities of the methodology adopted to compare bodies:

- Firstly, each machine tolerance does determine the maximum dimensional tolerance which could be achieved,
- Second, once the data has been treated, it has to be determined which is exactly the best machinery usage for determine the tolerance regarding the needs of the final use.

With regards to the first point, it has to be stated that CMM Machine does have a tolerance of 0.001mm while the 3D Scan does provide a 0.04mm of tolerance. Also, in order to complement this information with regards to the second point, it has to be stated that CMM Machine only provides a profile of the whole body each time the process is performed, while the 3D Scan does provide the hole scanned body at once.

It should be taken into consideration, as well, that the CMM Machine does have a better tolerance for treating bodies and the fact that it is relatively easy to extract the data and exact points calculated and have the coordinates of a desired point, which allows a numerical comparison, while the 3D Scanned body is compared using the Solidworks software which provides the height difference between comparison, but it has not been possible to extract the relative height difference in a desired point.

Therefore, due to all the points taken into consideration until the current point, it is taken out that this project does have accomplished its objective to use different hardware in order to extract data information with regards to body comparison, and does provide a dual-comparison process, one using CMM Machine and the other with the 3D Scan but, as well, it has been also possible to compare both results at once.

Following, it can be seen in *Table 20* the general comparison for the process accuracies found along the different CMM Machine and SolidWorks comparison and, as well, in *Table 21* a summary of the whole project requirements, while *Illustration 41.- General equipment and software used alongside the project.* works as a general overview of the whole process of body comparison and data processing methodology.

*Table 20. Different process accuracies*

<i>Values in mm</i>	<b>CMM Machine</b>	<b>SolidWorks</b>
<b>Printing process accuracy</b>	2.0140%	1.8561%
<b>Thermoforming process wear</b>	0.89506%	2.6123%
<b>PVC Sheets comparison</b>	5.9826%	3.003%

<b>PC Sheets comparison</b>	1.8499%	6.663%
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*Table 21. Accomplishment of project requirements*

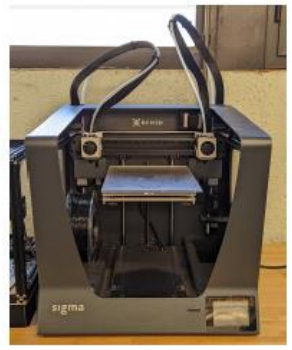
Project requirements	Detail	Accomplishment
AIM	Study the dimensional accuracy process of thermoforming, via 3D scanning and CMM hardware, and different software.	✓
METHODOLOGY	Performance of the thermoforming process	✓
	Usage of CMM to take data.	✓
	Usage of a 3D scan to take data.	✓
	Usage of a specific methodology path to treat CMM data.	✓
	Usage of a specific methodology path to treat 3D scanned data.	✓
EQUIPMENT	Mitutoyo model Crysta-Apex C544 coordinate measuring machine (CMM)	
	3D scanner EinScan Pro 2X.	
	Mitutoyo Surftest SV2000.	
	PC & PVC sheets.	
	Formech 450, Thermoforming Equipment	
	Microsoft Office	
	Solid Works	
	Geomagic Essentials	
	Shining 3D	
	PLA 3D printed die	
BCN Cura Sigma R19 3D printer		
MATERIALS	PC sheets	
	PVC sheets	
	PLA filament	
EXPERIMENTATION	Propose a valid CMM methodology analysis for the thermoformed die, PC and PVC data.	✓
	Propose a valid 3D Scanning methodology analysis for the thermoformed die, PC and PVC data.	✓
TIMING	Due to 06/2023.	✓
ANALYSIS RESULTS	Evaluate and quantify the die wear during the thermoforming process.	✓
	Evaluate and quantify the PC and PVC wear during the thermoforming process.	✓
	Obtain of an optimized methodology for treating CMM and/or 3D scanned data.	✓
COSTS	Correct budgeting of the whole process by evaluating, optimizing and minimizing overall project costs.	✓

Data process Starting point Data creation

1

Equipment

3D Printer  
BCN3D Cura



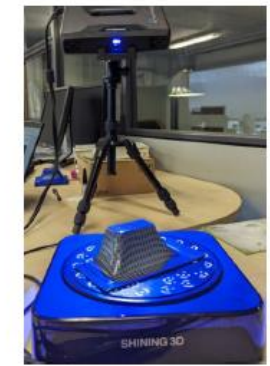
Thermoforming machine  
Formech 450



CMM Machine  
Mitutoyo Crysta-Apex C544



3D Scan  
Einscan Pro 2X



Software



Data process Data treatment Data comparison

2

Software

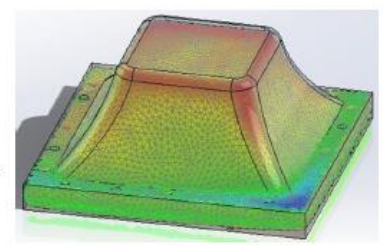
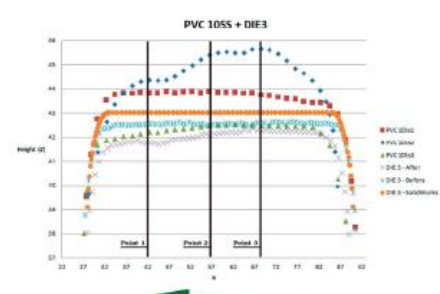
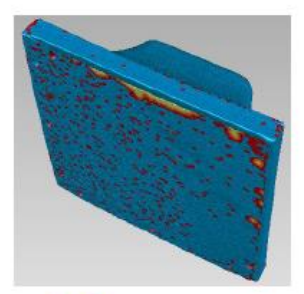
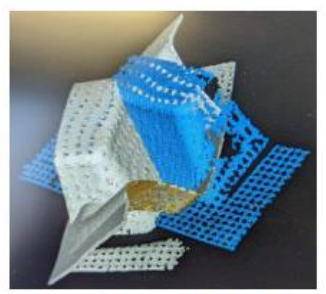


Illustration 41.- General equipment and software used alongside the project.

## 9. Bibliography

- [1] *Thermoforming: What Is It? How Does It Work? Types & Process*. (n.d.). Retrieved December 2, 2022, from <https://www.iqsdirectory.com/articles/vacuum-forming/thermoforming.html>
- [2] Productive Plastics, I. (n.d.). *Plastic Thermoforming, Pressure Forming, Vacuum Forming – What’s the Difference? | Productive Plastics*. Retrieved December 14, 2022, from <https://www.productiveplastics.com/plastic-thermoforming-pressure-forming-vacuum-forming-whats-the-difference/>



## 10. Annexes

### Annex I.- Thermoforming. General definition

By definition, thermoforming is a plastic manufacturing process which heats a two-dimensional clamped thermoplastic sheet, using pressure or force of a vacuum to a mold, stretching it and creating a three-dimensional shape, following the mold silhouette and then cooling the sheet until it solidifies.

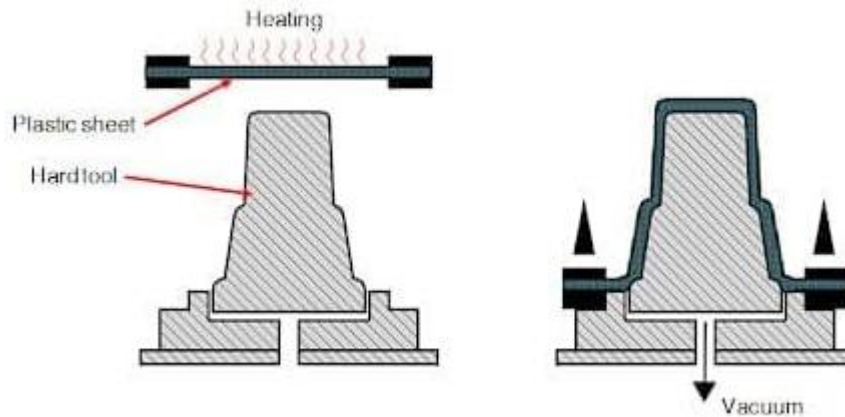
Therefore, the main elements to take thermoforming into reality are:

- Heating machine,
- Mold with the desired form,
- A thermoplastic sheet.

Even though they may be variants, the thermoforming process is performed, broadly, as follows:

- 1) A thermoplastic sheet, which should have a greater width and length than the final product, is clamped into a holding device of a heating machine,
- 2) The thermoplastic sheet is heated through heat convection or radiation until the desired temperature,
- 3) While the thermoplastic sheet is being heated, the mold should already be in position, fixed,
- 4) Once the sheet is heated, it is pressed into or stretch over the mold using vacuum pressure, air pressure or mechanical force.
- 5) Since the thermoplastic sheet has been soften through temperature, it conforms to the mold's shape,
- 6) The thermoplastic sheet is held in place until it cools,
- 7) Then, if it is a finished product, the excess material is trimmed away and stored.

Following, a simplified illustration of the process is exposed:



*Illustration 42.- Thermoforming process*

Important characteristics of a thermoforming conformation process, as stated by the leading thermoforming manufacturers and companies [1] are:

- The usage of a thermoplastic as a plastic to be conformed is of a huge importance since they have the capabilities which allow them to be deformed many times without losing or altering their main chemical properties, if heated under a certain temperature. Therefore, they can be reprocessed, which gives them the capability of being recyclable. Thus, all the waste material trimmed in the process is recycled.
- The temperature desired in order to be able to recast and reprocess the thermoplastic sheet, also known as the forming temperature, is a temperature located below its melting temperature and above the glass-transition temperature. Under this range of temperature, the thermoplastic material can be defined as a “soft and pliable rubber-like material”.

The following sections are the explanation of the main thermoforming elements used in the current thermoforming process studied and the specifically thermoforming process performed is explained in section “2.5. Thermoforming as a manufacturing process”.

Thermoforming manufacturing process can be classified depending on how the heated sheet is stretch over the mold and regarding the material thickness:

- Vacuum forming: It happens by pulling/drawing the mold with a vacuum from underneath. Suitable for non-complex geometrical pieces, since it is difficult to control uniform vacuum pressure, which can compromise material thickness.

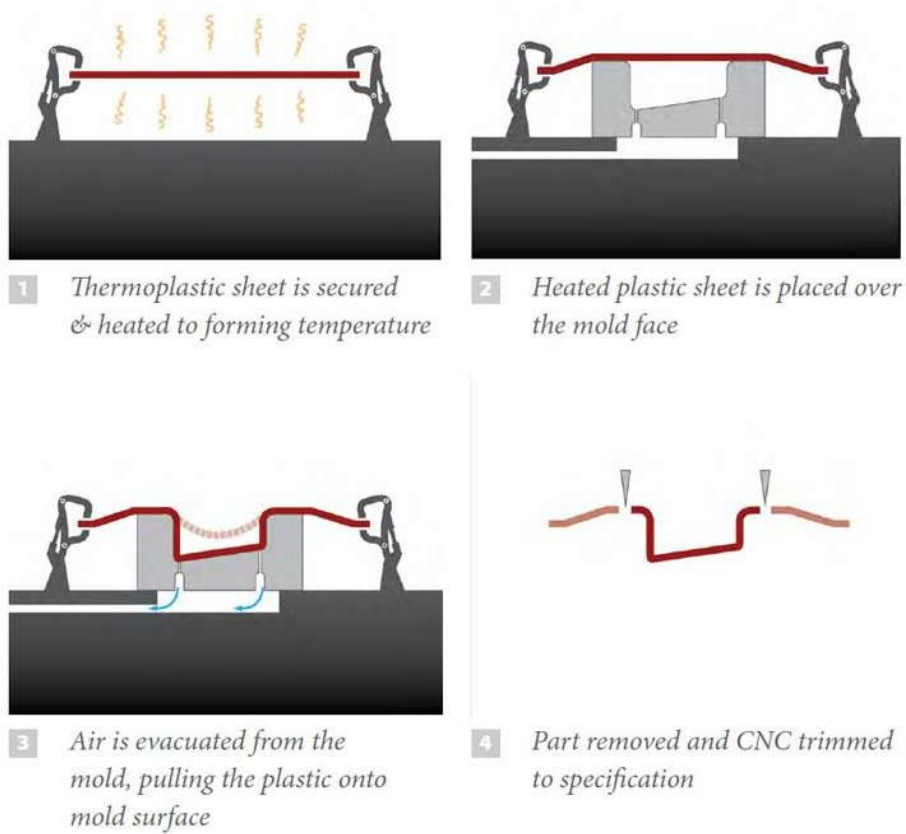


Illustration 43.- Vacuum forming process. Source: Copied from internet.

- Pressure forming: It happens by applying air above the mold and vented from below, to form shape. In this particular case, air pressure makes the possibility of sharper corners, textured surfaces and, in general, greater detail manufactured finished products. Suitable for complex designs, as stated by the thermoforming manufacturer Productive Plastics, Inc. [2].

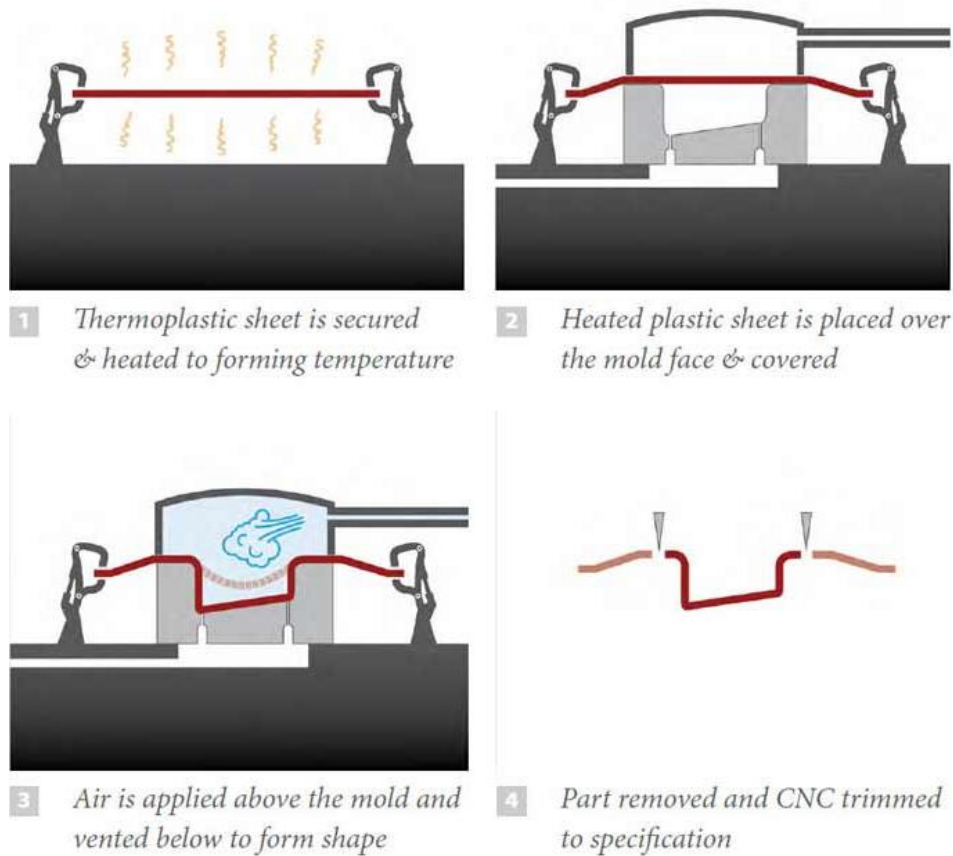


Illustration 44.- Pressure forming process. Source: Copied from internet.

- Heavy-gauge thermoforming production: this term is used when the thickness material is between 1.5 and 12.7mm. It allows producing complex products with smoother shapes, which can end up having an attractive appearance for end-applications.
- Thin-gauge thermoforming production: this term is used when the thickness material is less than 1.5mm.

In order to process a successful thermoforming process, the following parameters need to be optimized and controlled:

- Forming temperature,
- Mold material and temperature,
- Vacuum and/or air pressure,
- Liquid or air coolant flow rate,
- Liquid or air coolant temperature.

Just like all manufacturing processes, tool management and design are key for a successful manufacturing and dimensional accuracy.

Even though the project itself does not evolve around thermoforming, the pros and cons of thermoforming are mentioned below, in order to give a wider view of the manufacturing process, as well as its main uses:

The main benefits of thermoforming are: low cost and tooling costs, durability, design and development, while regarded disadvantages could be that molded-in components like screws and fasteners cannot be included, thickness could be an issue if it should be assured all along the final product, since it may not be even across all surfaces, individual part costs may be higher than injection molding and, even though thermoformed plastics can be recycled, thermoforming process does produce a good amount of waste which, should be reassembled and retreated in order to be reused, which gives an extra cost to the process.

Since there are different varieties for the thermoforming process, and a wide range of thickness for the thermoplastic materials, there are, as well, a wide variety of products which are created using this method.

Given that thermoplastic allows producing complex and smooth shapes but also needs to have the front side to be the same as the back side, one good example are chassis car parts, created with a heavy-gauge production. They can easily be designed and processed by adjusting a mold, which will give the final desired shape with ease while maintaining a high-impact resistance, durable and shape complex product, which will have a harmonic design, without compromising the whole manufacturing process.

Other products to be mentioned are:

- Thermoplastic cups,
- Musical instruments,
- Food packaging,
- Water bottles and carbonated soft drinks

Plastic thermoforming often outperforms other processes and materials such as fiberglass FRP, metal or injection molding.

Part thickness distribution may be improved through pre-forming of the plastic sheet before it is drawn to the mold cavity.

Basically, thermoforming is to take a warm sheet of plastic and place it on a mold such that it takes on the desired form. Even though the process is simple and efficient, it produces highly durable and resilient products, which are easily disposable and recyclable or long-lasting.

## Annex II.- Thermoforming machine used

In order to perform the thermoforming process, it has been used a thermoforming vacuum machine by Formech manufacturer (Formech 450, Thermoforming Equipment).

In the following illustration, the already explained main important parts of a thermoforming vacuum machine are pointed out.

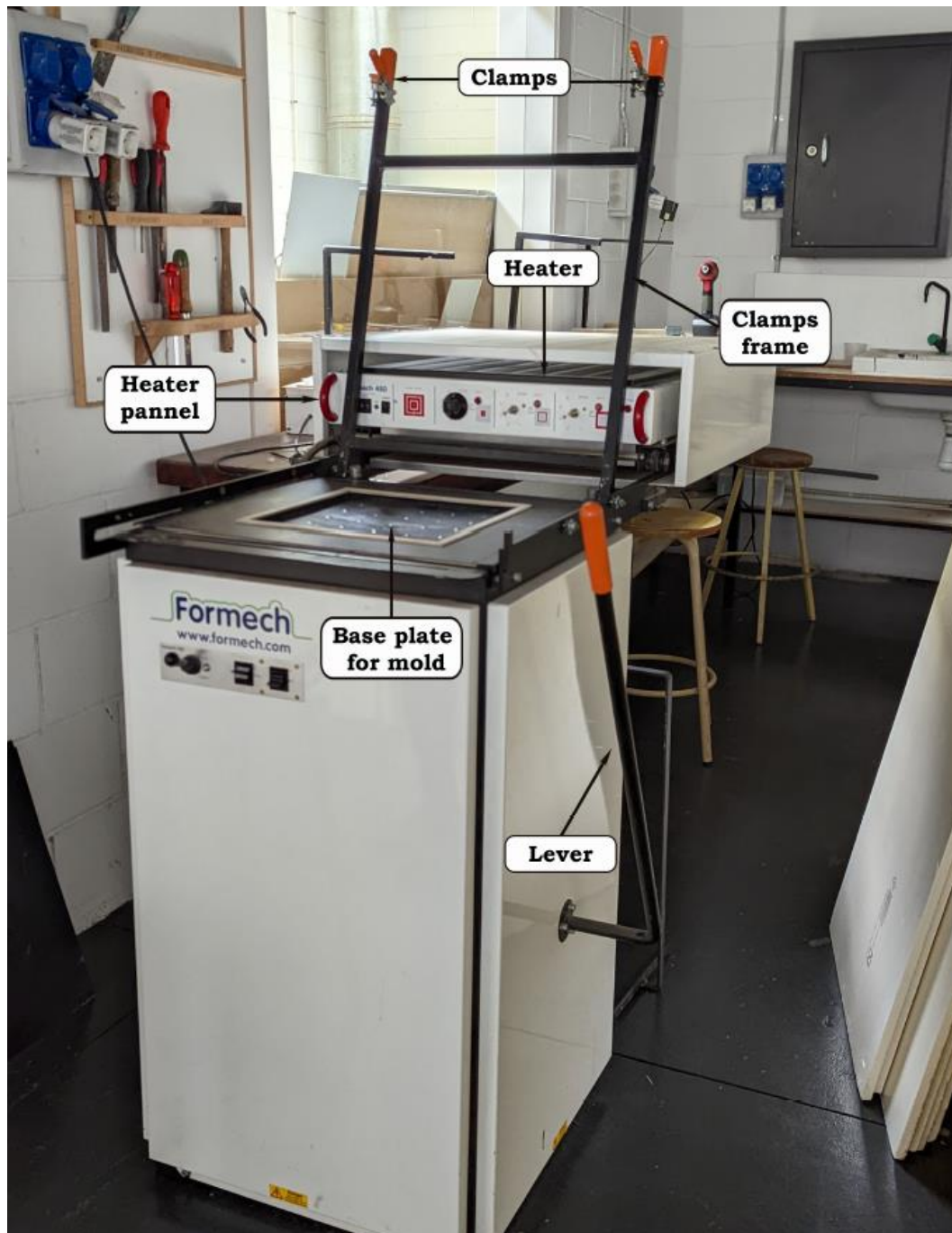


Illustration 45.- Thermoforming Machine

### Annex III.- 3D printed mold (DIE3)

For the thermoforming manufacturing process, molds are carefully designed by the manufacturer to create the required profile of the finished product and, as well, to ensure that the vacuum does homogenize the product. In this case, the mold design has also been a big factor and, because of it, the mold used in this thermoforming process studied is an optimized 3<sup>rd</sup> design, which has named DIE3.

Molds are usually made of:

- Wood: cheap, easily to shape which enables geometrical difficult final forms without high costs,
- Fiberglass: inexpensive and permanent but long cooling cycle,
- Aluminum: high temperature control.

In this projects case, it is a 3D printed plastic PLA mold. The mold used for the process has been 3D printed. Firstly, the mold was designed in SolidWorks and then given the 3D printing specifications in BCN3D Cura software. Then, the mold already designed was 3D printed using the BCN3D Cura 3D printed equipment.



*Illustration 46.- BCN3D Cura Printer*

As a material, Ø2.85mm PLA commercial filament was used and, in the following table, the printing specifications about the 3D printer are detailed.

*Table 22. BCN3D Cura Printer specifications*

<b>Specifications</b>	<b>Used</b>
Manufacturing technology	Fused Filament Fabrication (FFF)
Architecture	Independent dual extruder (IDEX)
General dimensions	690 x 530 x 900 mm (fully assembled)
Weight	37 kg (without filament spools)
Printing volume	420 x 300 x 400 mm
Number of extruders	2
Nozzle diameter	0.4 (installed) / 0.6 / 0.8 / 1mm / Hotend X: 0.6
Layer height	0.05-0.5 mm (depending on the nozzle diameter)
Operating temperature	15°C -35°C
Maximum extruder temperature	300°C
Maximum printing surface temperature	120°C
Filament diameter	2.85mm
Compatible material	PLA, PVA, PET-G, TPU, ABS, PP, PA. Fiber filled materials. Only with Hotend X (0,6mm):
Compatible files	G-code
Software preparation files	BCN3D Cura



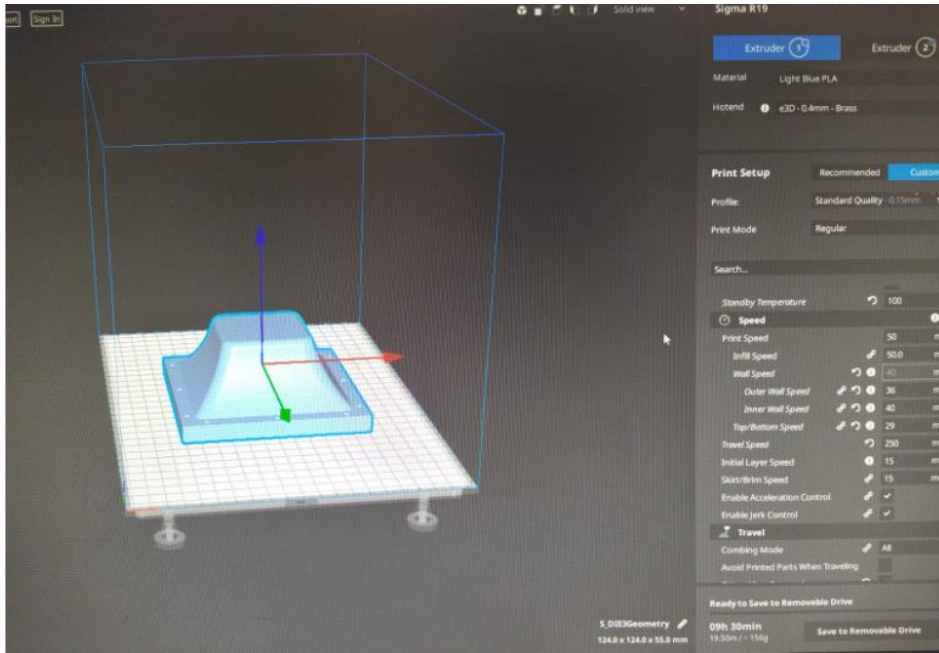


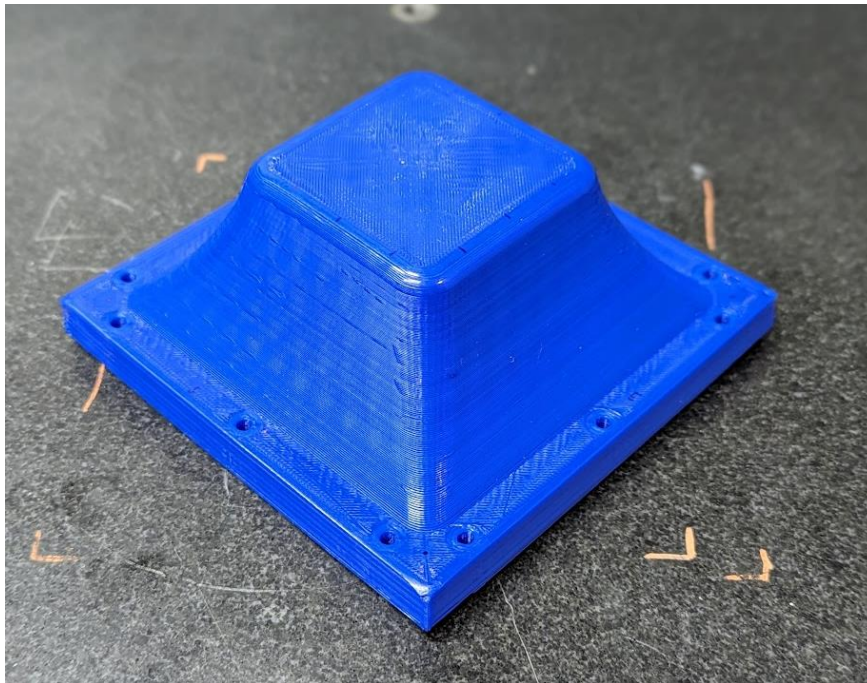
Illustration 47. BCN3D Cura software user interface

Besides, in Table 2, the most important specifications for the study of the mold lifespan and its shear during thermoforming are detailed, as well as a photo of the final mold printed.

Table 23.- BCN3D Cura set up printing specifications.

Specifications	Parameters
Quality	
Line Width	0,35 mm
Wall thickness	1 mm
Layer Height	0,3 mm
Top/Bottom thickness	1 mm
Top Layers	6
Bottom layers	4
Top/Bottom pattern	Zig Zag
Infill	
Infill density	15%
Infill line distance	5,6 mm
Infill pattern	Grid

Material	
Printing temperature	205°C
Printing temperature initial layer	210°C
Speed	
Print speed	50 mm/s
Infill speed	50 mm/s
Wall speed	40 mm/s
Inner Wall speed	40 mm/s
Outer wall speed	36 mm/s

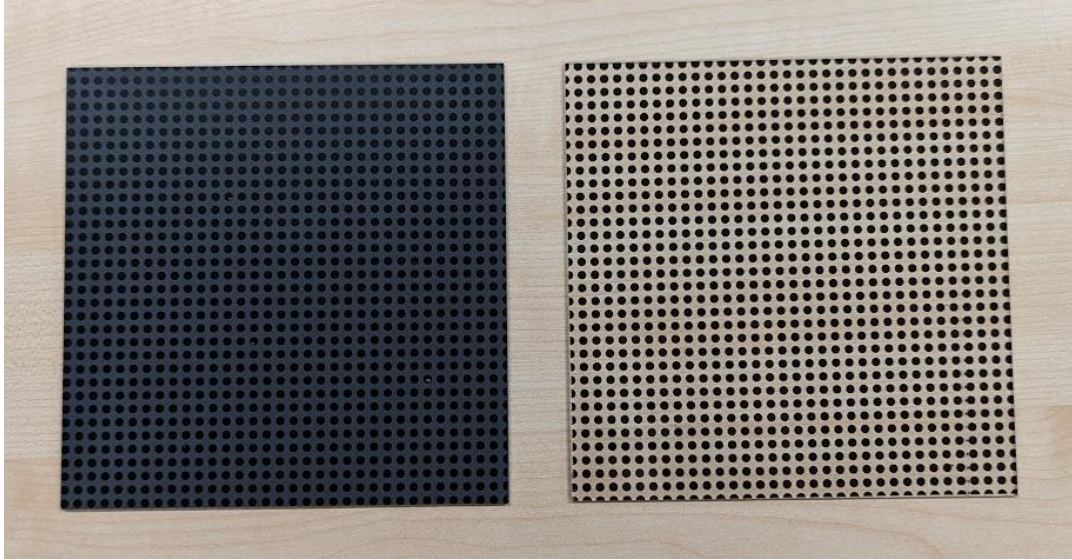


*Illustration 48.- DIE3 final form*

## Annex IV.- Thermoplastic sheets

The initial material used for the current thermoforming process is:

- PC sheets of 150x150x1.5mm
- PVC sheets of 150x150x1.5mm



*Illustration 49.- Initial thermoplastic sheets*

The choosing of PC and PVC for the thermoforming process is that they both are widely used in thermoforming, because of their forming capabilities. Following, their thermoforming temperatures:

*Table 24.- Thermoforming temperatures.*

<b>Material</b>	<b>Thermoforming temperature [°C]</b>
Polycarbonate (PC)	175 – 230
Polyvinyl Chloride (PVC)	110 - 150

Polyvinyl Chloride film is created from suspension polymerization, and it is one of the most used materials in the construction industry due to its properties: excellent resistance to extreme environmental conditions, since impact and grease to fire. PVC is, as well, a good electrical insulator and there are a wide range of PVC varieties. Even though its uses, end-applications and properties do vary because of its wide range of manufacturing processes to adapt the material to the final product, following are some important end-applications, and properties:

- Tubes and materials for piping systems,
- Cables, wires and electrical conducts,

- Clothing accessories,
- Chemical, hot and cold delivery systems.

*Table 25.- PVC main properties.*

<b>Property</b>	<b>Value</b>
Technical Name	Polyvinyl Chloride (PVC)
Chemical Formula	(C <sub>2</sub> H <sub>3</sub> Cl) <sub>n</sub>
Melting Temperature	212 - 500 °F (100 - 260°C)
Heat Deflection Temperature (HDT)	92 °C (198 °F)
Tensile Strength	Flexible PVC: 6.9 - 25 MPa (1000 - 3625 PSI) Rigid PVC: 34 - 62 MPa (4930 - 9000 PSI)
Specific Gravity	1.35 - 1.45

Polycarbonate, as well, is one of the most used plastics in many different fields. PC is a dimensionally stable, high impact strength and tough material which does also have good electrical insulation resistance and good chemical properties.

Some of its end-applications and properties are:

- Appliances and electronic devices,
- Automotive parts,
- Construction materials,
- Sunglasses.

*Table 26.- PC main properties.*

<b>Property</b>	<b>Value</b>
Technical Name	Polycarbonate (PC)
Chemical Formula	C <sub>15</sub> H <sub>16</sub> O <sub>2</sub>
Melt Temperature	288-316 °C (550-600 °F)
Typical Mold Temperature	82 - 121 °C (180 - 250 °F)
Heat Deflection Temperature (HDT)	140 °C (284 °F) at 0.46 MPa (66 PSI)

Tensile Strength	59 MPa (8500 PSI)
------------------	-------------------

## Annex V – Data comparison excel

Following, represented the different data analysis sheets are represented. In order:

1. Data comparison sheet explanation,
2. DIE3 different states comparison,
3. PC and PVC comparisons with DIE3 different states.

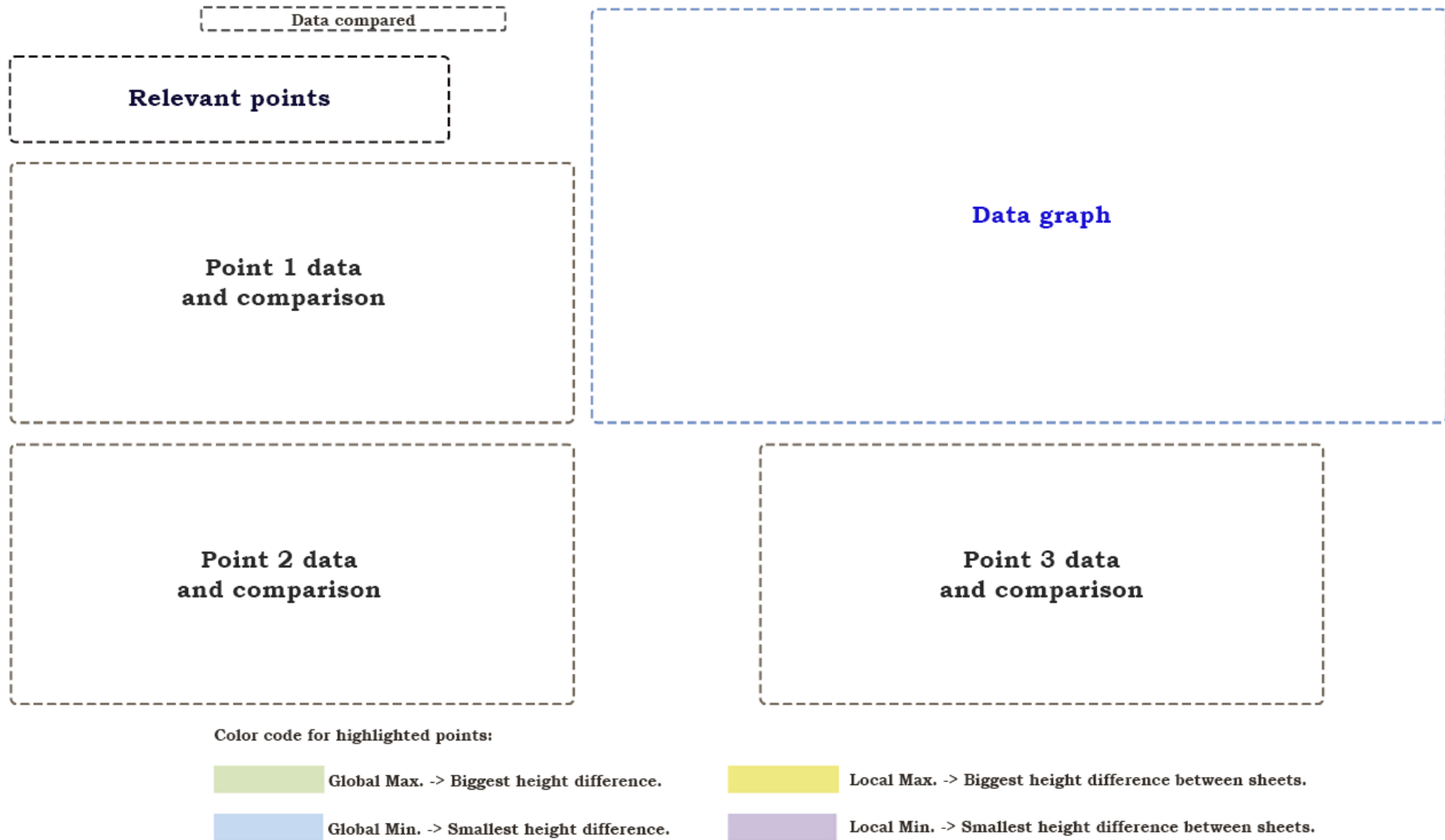


Illustration 50.- Data comparison sheet explanation.

Data comparison - DIE 3

	(x)	Reason
Point 1	37	Left-side / Lowest
Point 2	54	Around the middle of the top side
Point 3	72	Right-side

Point 1

	Original (x)	Standardised (x)	Height (z)
DIE 3 - Before	96,48197	37,65469	42,7741
DIE 3 - After	146,0619	37,60005	41,96164
DIE 3 - SolidWorks	47	37,5	43

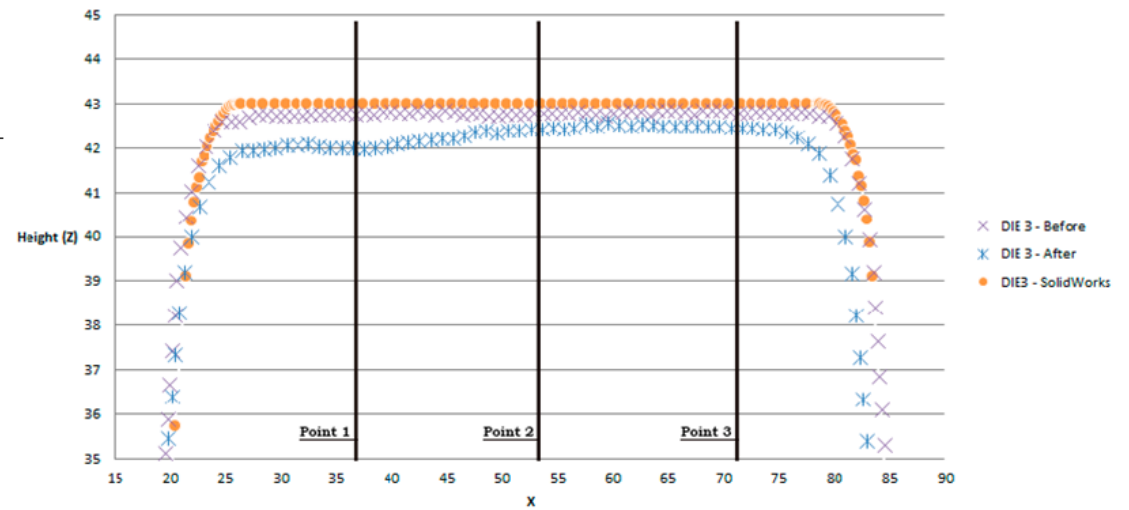
	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
DIE 3 - Before		0,81246	-0,2259
DIE 3 - After	-0,81246		-1,03836
DIE 3 - SolidWorks	0,2259	1,03836	

Point 2

	Original (x)	Standardised (x)	Height (z)
DIE 3 - Before	113,35245	54,52517	42,79441
DIE 3 - After	163,08201	54,62016	42,45003
DIE 3 - SolidWorks	64	54,5	43

	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
DIE 3 - Before		0,34438	-0,20559
DIE 3 - After	-0,34438		-0,54997
DIE 3 - SolidWorks	0,20559	0,54997	

DIE 3



Point 3

	Original (x)	Standardised (x)	Height (z)
DIE 3 - Before	131,01169	72,18441	42,79005
DIE 3 - After	181,13457	72,67272	42,44978
DIE 3 - SolidWorks	82	72,5	43

	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
DIE 3 - Before		0,34027	-0,20995
DIE 3 - After	-0,34027		-0,55022
DIE 3 - SolidWorks	0,20995	0,55022	

Illustration 51.- DIE 3 Different states comparison.

Data comparison - PC90 sheets + DIE 3

	(x)	Reason
Point 1	37	Left-side
Point 2	56	Around the middle of the top
Point 3	77	Right-side

Point 1

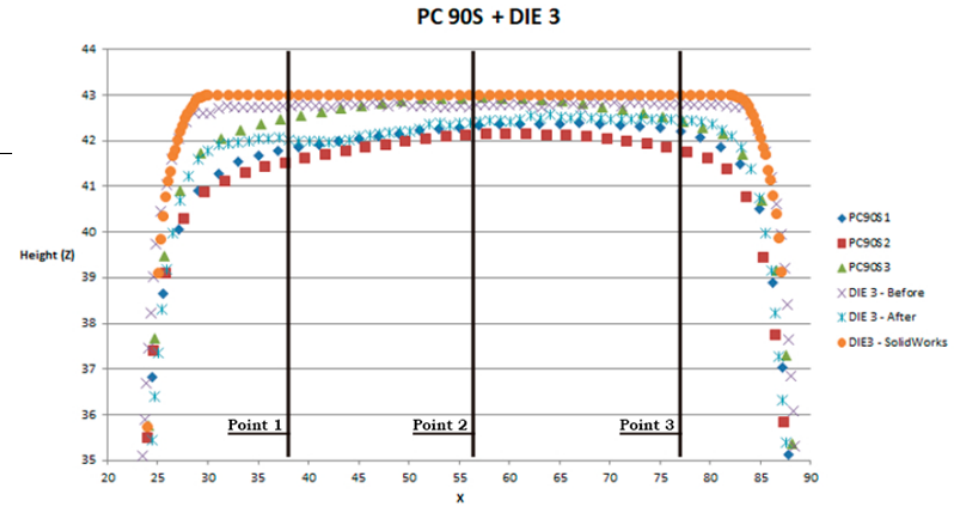
	Original (x)	Standardised (x)	Height (z)
PC90s1	93,00406	37,00406	41,77484
PC90s2	93,65672	37,65672	41,51638
PC90s3	93,26703	37,26703	42,4801
DIE 3 - Before	92,47215	37,47215	42,75752
DIE 3 - After	141,04761	37,04761	42,07363
DIE 3 - SolidWorks	43	37	43

	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC90s1		0,25846	-0,70526	-0,98268	-0,29879	-1,22516
PC90s2	-0,25846		-0,96372	-1,24114	-0,55725	-1,48362
PC90s3	0,70526	0,96372		-0,27742	0,40647	-0,5199
DIE 3 - Before	0,98268	1,24114	0,27742		0,68389	-0,24248
DIE 3 - After	0,29879	0,55725	-0,40647	-0,68389		-0,92637
DIE 3 - SolidWorks	1,22516	1,48362	0,5199	0,24248	0,92637	

Point 2

	Original (x)	Standardised (x)	Height (z)
PC90s1	112,99638	56,99638	42,33679
PC90s2	111,64757	55,64757	42,11637
PC90s3	113,26266	57,26266	42,94635
DIE 3 - Before	111,75167	56,75167	42,77649
DIE 3 - After	160,0811	56,0811	42,40048
DIE 3 - SolidWorks	62	56	43

	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC90s1		0,22042	-0,60956	-0,4397	-0,06369	-0,66321
PC90s2	-0,22042		-0,82998	-0,66012	-0,28411	-0,88363
PC90s3	0,60956	0,82998		0,16986	0,54587	-0,05365
DIE 3 - Before	0,4397	0,66012	-0,16986		0,37601	-0,22351
DIE 3 - After	0,06369	0,28411	-0,54587	-0,37601		-0,59952
DIE 3 - SolidWorks	0,66321	0,88363	0,05365	0,22351	0,59952	



Point 3

	Original (x)	Standardised (x)	Height (z)
PC90s1	133,00053	77,00053	42,20298
PC90s2	133,65279	77,65279	41,75432
PC90s3	133,27561	77,27561	42,42527
DIE 3 - Before	132,61797	77,61797	42,82008
DIE 3 - After	181,13457	77,13457	42,44978
DIE 3 - SolidWorks	83	77	43

	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC90s1		0,44866	-0,22229	-0,6171	-0,2468	-0,79702
PC90s2	-0,44866		-0,67095	-1,06576	-0,69546	-1,24568
PC90s3	0,22229	0,67095		-0,39481	-0,02451	-0,57473
DIE 3 - Before	0,6171	1,06576	0,39481		0,3703	-0,17992
DIE 3 - After	0,2468	0,69546	0,02451	-0,3703		-0,55022
DIE 3 - SolidWorks	0,79702	1,24568	0,57473	0,17992	0,55022	

Illustration 52.- PC90S + DIE3 comparison



Data comparison - PC105 sheets + DIE 3

	(x)	Reason
Point 1	35	Left-side
Point 2	56	Around the middle of the top
Point 3	77	Right-side

Point 1

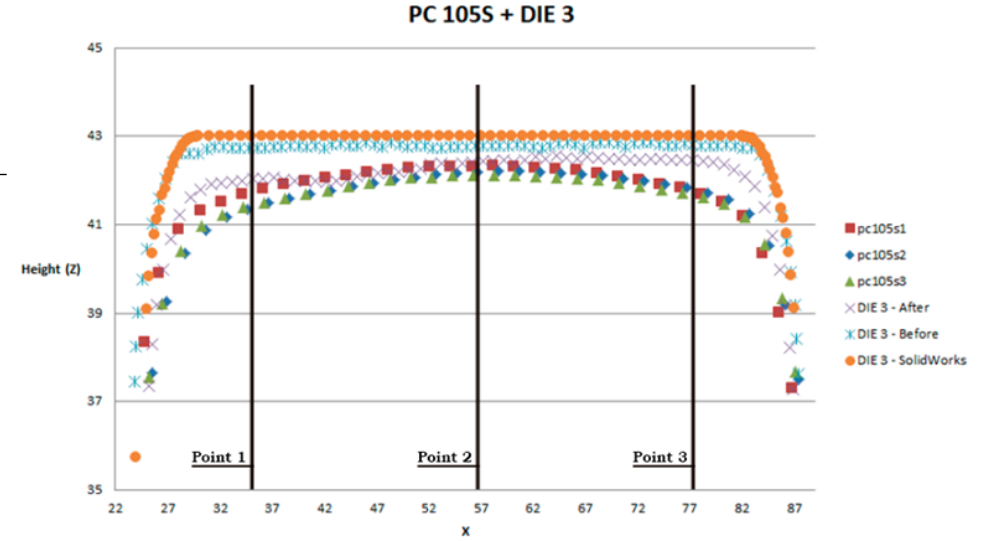
	Original (x)	Standardised (x)	Height (z)
PC105s1	89,44558	34,14558	41,69068
PC105s2	90,00115	34,70115	41,35252
PC105s3	92,58629	36,28629	41,48536
DIE 3 - Before	139,04023	35,17064	42,04889
DIE 3 - After	90,87097	35,57097	42,74079
DIE 3 - SolidWorks	41	35	43

	PC105s1	PC105s2	PC105s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC105s1		0,33816	0,20532	-0,35821	-1,05011	-1,30932
PC105s2	-0,33816		-0,13284	-0,69637	-1,38827	-1,64748
PC105s3	-0,20532	0,13284		-0,56353	-1,25543	-1,51464
DIE 3 - Before	0,35821	0,69637	0,56353		-0,6919	-0,95111
DIE 3 - After	1,05011	1,38827	1,25543	0,6919		-0,25921
DIE 3 - SolidWorks	1,30932	1,64748	1,51464	0,95111	0,25921	

Point 2

	Original (x)	Standardised (x)	Height (z)
PC105s1	111,42779	56,12779	42,32426
PC105s2	111,98365	56,68365	42,19088
PC105s3	112,57352	56,27352	42,11289
DIE 3 - Before	160,0811	56,21151	42,40048
DIE 3 - After	111,75167	56,45167	42,77649
DIE 3 - SolidWorks	62	56	43

	PC105s1	PC105s2	PC105s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC105s1		0,13338	0,21137	-0,07622	-0,45223	-0,67574
PC105s2	-0,13338		0,07799	-0,2096	-0,58561	-0,80912
PC105s3	-0,21137	-0,07799		-0,28759	-0,6636	-0,88711
DIE 3 - Before	0,07622	0,2096	0,28759		-0,37601	-0,59952
DIE 3 - After	0,45223	0,58561	0,6636	0,37601		-0,22351
DIE 3 - SolidWorks	0,67574	0,80912	0,88711	0,59952	0,22351	



Point 3

	Original (x)	Standardised (x)	Height (z)
PC105s1	133,43271	78,13271	41,69102
PC105s2	131,99049	76,69049	41,83658
PC105s3	134,58184	78,28184	41,61455
DIE 3 - Before	181,13457	77,26498	42,44978
DIE 3 - After	132,61797	77,31797	42,82008
DIE 3 - SolidWorks	83	77	43

	PC105s1	PC105s2	PC105s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC105s1		-0,14556	0,07647	-0,75876	-1,12906	-1,30898
PC105s2	0,14556		0,22203	-0,6132	-0,9835	-1,16342
PC105s3	-0,07647	-0,22203		-0,83523	-1,20553	-1,38545
DIE 3 - Before	0,75876	0,6132	0,83523		-0,3703	-0,55022
DIE 3 - After	1,12906	0,9835	1,20553	0,3703		-0,17992
DIE 3 - SolidWorks	1,30898	1,16342	1,38545	0,55022	0,17992	

Illustration 53.- PC105S + DIE3 comparison

DIMENSIONAL STUDY OF THE WEAR AND LIFE OF 3D PRINTED MOLDS USED TO DEFORM SHEETS THROUGH THERMOFORMING.  
USE PROTOCOLS AND DATA PROCESSING METHODOLOGY.

Data comparison - PC120 sheets + DIE 3

	(x)	Reason
Point 1	42	Left-side / Lowest
Point 2	56	Around the middle of the top
Point 3	75	Right-side

**Point 1**

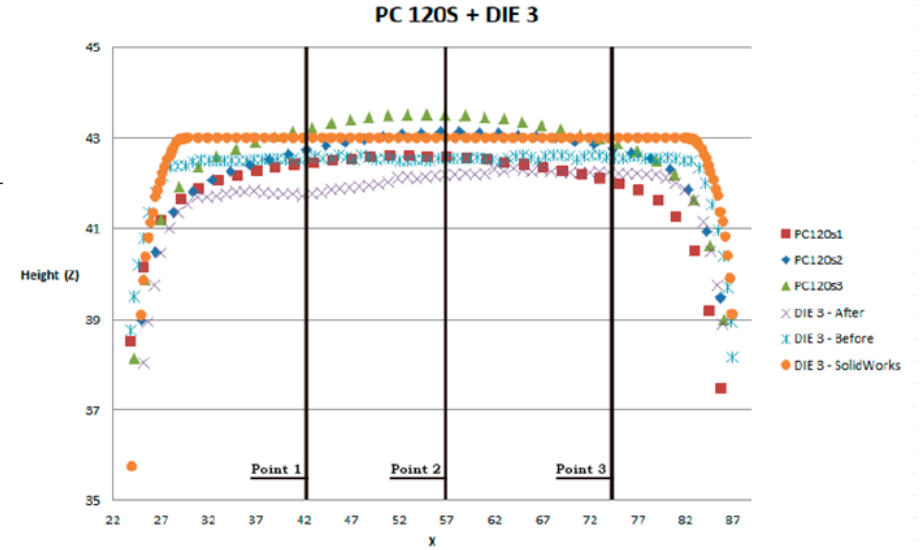
	Original (x)	Standardised (x)	Height (z)
PC120s1	100,22589	43,12589	42,44733
PC120s2	42,74348	42,39619	42,74348
PC120s3	102,02536	42,92536	43,23922
DIE 3 - Before	98,08896	42,48896	42,56264
DIE 3 - After	42,89705	42,89705	41,74738
DIE 3 - SolidWorks	48	42	43

	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC120s1		-0,29615	-0,79189	-0,11531	0,69995	-0,55267
PC120s2	0,29615		-0,49574	0,18084	0,9961	-0,25652
PC120s3	0,79189	0,49574		0,67658	1,49184	0,23922
DIE 3 - Before	0,11531	-0,18084	-0,67658		0,81526	-0,43736
DIE 3 - After	-0,69995	-0,9961	-1,49184	-0,81526		-1,25262
DIE 3 - SolidWorks	0,55267	0,25652	-0,23922	0,43736	1,25262	

**Point 2**

	Original (x)	Standardised (x)	Height (z)
PC120s1	114,2259	57,1259	42,57239
PC120s2	43,13043	56,3927	43,13043
PC120s3	116,02247	56,92247	43,51226
DIE 3 - Before	111,75167	56,15167	42,53591
DIE 3 - After	56,91155	56,91155	42,18842
DIE 3 - SolidWorks	62	56	43

	PC90s1	PC90s2	PC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC120s1		-0,55804	-0,93987	0,03648	0,38397	-0,42761
PC120s2	0,55804		-0,38183	0,59452	0,94201	0,13043
PC120s3	0,93987	0,38183		0,97635	1,32384	0,51226
DIE 3 - Before	-0,03648	-0,59452	-0,97635		0,34749	-0,46409
DIE 3 - After	-0,38397	-0,94201	-1,32384	-0,34749		-0,81158
DIE 3 - SolidWorks	0,42761	-0,13043	-0,51226	0,46409	0,81158	



**Point 3**

	Original (x)	Standardised (x)	Height (z)
PC120s1	132,23708	75,13708	41,97238
PC120s2	42,66764	76,39585	42,66764
PC120s3	134,02915	74,92915	42,86445
DIE 3 - Before	131,01169	75,41169	42,54947
DIE 3 - After	75,96335	75,96335	42,21908
DIE 3 - SolidWorks	81	75	43

	PC120s1	PC120s2	PC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PC120s1		-0,69526	-0,89207	-0,57709	-0,2467	-1,02762
PC120s2	0,69526		-0,19681	0,11817	0,44856	-0,33236
PC120s3	0,89207	0,19681		0,31498	0,64537	-0,13555
DIE 3 - Before	0,57709	-0,11817	-0,31498		0,33039	-0,45053
DIE 3 - After	0,2467	-0,44856	-0,64537	-0,33039		-0,78092
DIE 3 - SolidWorks	1,02762	0,33236	0,13555	0,45053	0,78092	

Illustration 54.- PC120S + DIE3 comparison

Data comparison - PVC90 sheets + DIE 3

	(x)	Reason
Point 1	36	Left-side
Point 2	60	Around the middle of the top
Point 3	81	Right-side

**Point 1**

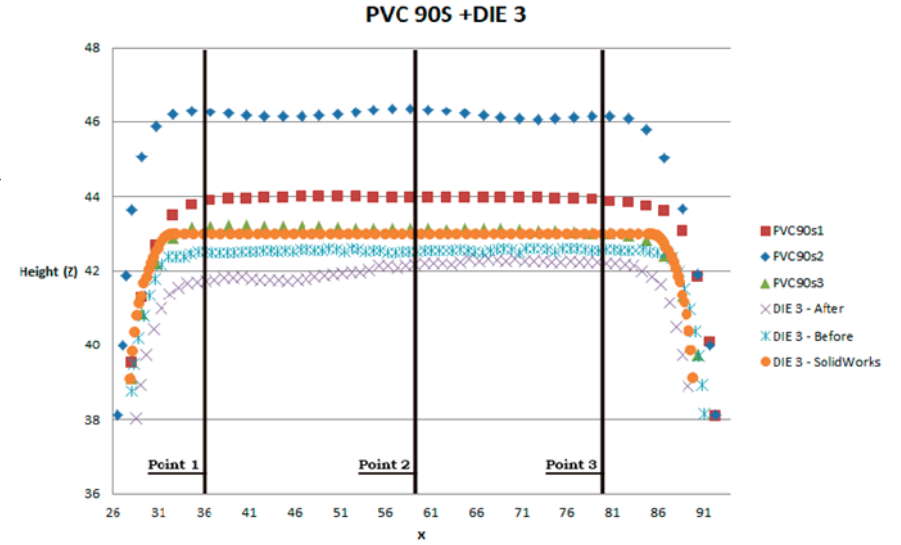
	Original (x)	Standardised (x)	Height (z)
PVC90s1	131,66562	36,76562	43,89898
PVC90s2	131,66562	36,76562	46,27174
PVC90s3	131,66562	36,76562	43,21443
DIE 3 - Before	87,6619	36,22177	42,50665
DIE 3 - After	137,04126	36,27627	41,72158
DIE 3 - SolidWorks	39	36	43

	PVC90s1	PVC90s2	PVC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC90s1		-2,37276	0,68455	1,39233	2,1774	0,89898
PVC90s2	2,37276		3,05731	3,76509	4,55016	3,27174
PVC90s3	-0,68455	-3,05731		0,70778	1,49285	0,21443
DIE 3 - Before	-1,39233	-3,76509	-0,70778		0,78507	-0,49335
DIE 3 - After	-2,1774	-4,55016	-1,49285	-0,78507		-1,27842
DIE 3 - SolidWorks	-0,89898	-3,27174	-0,21443	0,49335	1,27842	

**Point 2**

	Original (x)	Standardised (x)	Height (z)
PVC90s1	155,66941	60,76941	43,97494
PVC90s2	155,66941	60,76941	46,3338
PVC90s3	155,66941	60,76941	43,1218
DIE 3 - Before	111,75167	60,31154	42,53591
DIE 3 - After	161,08114	60,31615	42,18842
DIE 3 - SolidWorks	63	60	43

	PVC90s1	PVC90s2	PVC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC90s1		-2,35886	0,85314	1,43903	1,78652	0,97494
PVC90s2	2,35886		3,212	3,79789	4,14538	3,3338
PVC90s3	-0,85314	-3,212		0,58589	0,93338	0,1218
DIE 3 - Before	-1,43903	-3,79789	-0,58589		0,34749	-0,46409
DIE 3 - After	-1,78652	-4,14538	-0,93338	-0,34749		-0,81158
DIE 3 - SolidWorks	-0,97494	-3,3338	-0,1218	0,46409	0,81158	



**Point 3**

	Original (x)	Standardised (x)	Height (z)
PVC90s1	175,67224	80,77224	43,86443
PVC90s2	175,67224	80,77224	46,1576
PVC90s3	175,67224	80,77224	43,00228
DIE 3 - Before	132,61797	81,17784	42,5795
DIE 3 - After	182,1375	81,37251	42,19492
DIE 3 - SolidWorks	84	81	43

	PVC90s1	PVC90s2	PVC90s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC90s1		-2,29317	0,86215	1,28493	1,66951	0,86443
PVC90s2	2,29317		3,15532	3,5781	3,96268	3,1576
PVC90s3	-0,86215	-3,15532		0,42278	0,80736	0,00228
DIE 3 - Before	-1,28493	-3,5781	-0,42278		0,38458	-0,4205
DIE 3 - After	-1,66951	-3,96268	-0,80736	-0,38458		-0,80508
DIE 3 - SolidWorks	-0,86443	-3,1576	-0,00228	0,4205	0,80508	

Illustration 55.- PVC90S + DIE3 comparison

Data comparison - PVC105 sheets + DIE 3

	(x)	Reason
Point 1	42	Left-side
Point 2	57	Around the middle of the top
Point 3	68	Right-side

**Point 1**

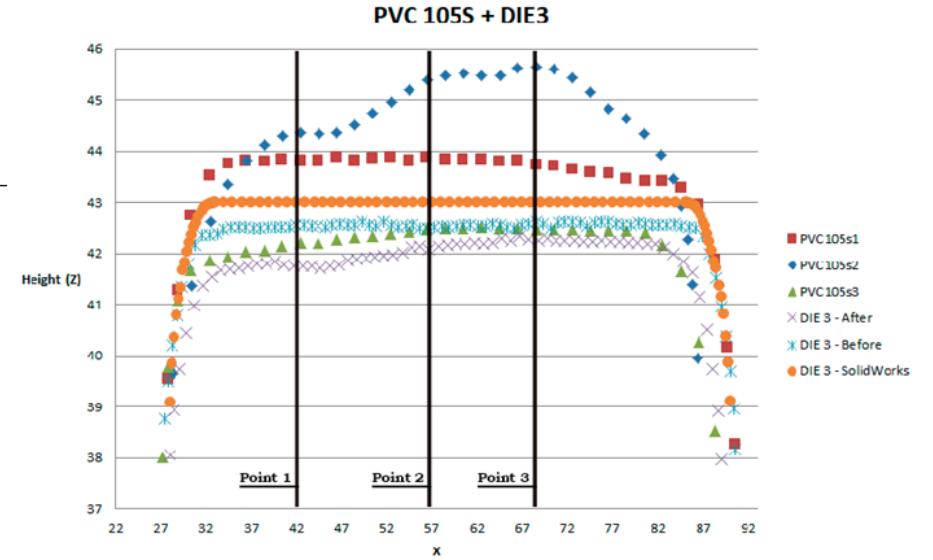
	Original (x)	Standardised (x)	Height (z)
PVC105s1	109,96757	42,46757	43,82694
PVC105s2	115,97279	42,47279	44,34901
PVC105s3	109,96757	42,46757	42,19976
DIE 3 - Before	94,07294	42,03281	42,54857
DIE 3 - After	144,05682	42,69183	41,74722
DIE 3 - SolidWorks	45	42	43

	PVC105s1	PVC105s2	PVC105s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC105s1		-0,52207	1,62718	1,27837	2,07972	0,82694
PVC105s2	0,52207		2,14925	1,80044	2,60179	1,34901
PVC105s3	-1,62718	-2,14925		-0,34881	0,45254	-0,80024
DIE 3 - Before	-1,27837	-1,80044	0,34881		0,80135	-0,45143
DIE 3 - After	-2,07972	-2,60179	-0,45254	-0,80135		-1,25278
DIE 3 - SolidWorks	-0,82694	-1,34901	0,80024	0,45143	1,25278	

**Point 2**

	Original (x)	Standardised (x)	Height (z)
PVC105s1	123,97968	56,47968	43,87491
PVC105s2	129,98431	56,48431	45,38421
PVC105s3	125,98246	58,48246	42,49725
DIE 3 - Before	109,34485	57,30472	42,51227
DIE 3 - After	159,07967	57,71468	42,14368
DIE 3 - SolidWorks	60	57	43

	PVC105s1	PVC105s2	PVC105s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC105s1		-1,5093	1,37766	1,36264	1,73123	0,87491
PVC105s2	1,5093		2,88696	2,87194	3,24053	2,38421
PVC105s3	-1,37766	-2,88696		-0,01502	0,35357	-0,50275
DIE 3 - Before	-1,36264	-2,87194	0,01502		0,36859	-0,48773
DIE 3 - After	-1,73123	-3,24053	-0,35357	-0,36859		-0,85632
DIE 3 - SolidWorks	-0,87491	-2,38421	0,50275	0,48773	0,85632	



**Point 3**

	Original (x)	Standardised (x)	Height (z)
PVC105s1	135,99083	68,49083	43,72405
PVC105s2	141,99795	68,49795	45,65483
PVC105s3	135,99083	68,49083	42,47674
DIE 3 - Before	63,10378	68,5286	42,61637
DIE 3 - After	170,11166	68,74667	42,25718
DIE 3 - SolidWorks	71	68	43

	PVC105s1	PVC105s2	PVC105s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC105s1		-1,93078	1,24731	1,10768	1,46687	0,72405
PVC105s2	1,93078		3,17809	3,03846	3,39765	2,65483
PVC105s3	-1,24731	-3,17809		-0,13963	0,21956	-0,52326
DIE 3 - Before	-1,10768	-3,03846	0,13963		0,35919	-0,38363
DIE 3 - After	-1,46687	-3,39765	-0,21956	-0,35919		-0,74282
DIE 3 - SolidWorks	-0,72405	-2,65483	0,52326	0,38363	0,74282	

Illustration 56.- PVC105S + DIE3 comparison

Data comparison - PVC120 sheets + DIE 3

	(x)	Reason
Point 1	42	Left-side
Point 2	57	Around the middle of the top
Point 3	77	Right-side

**Point 1**

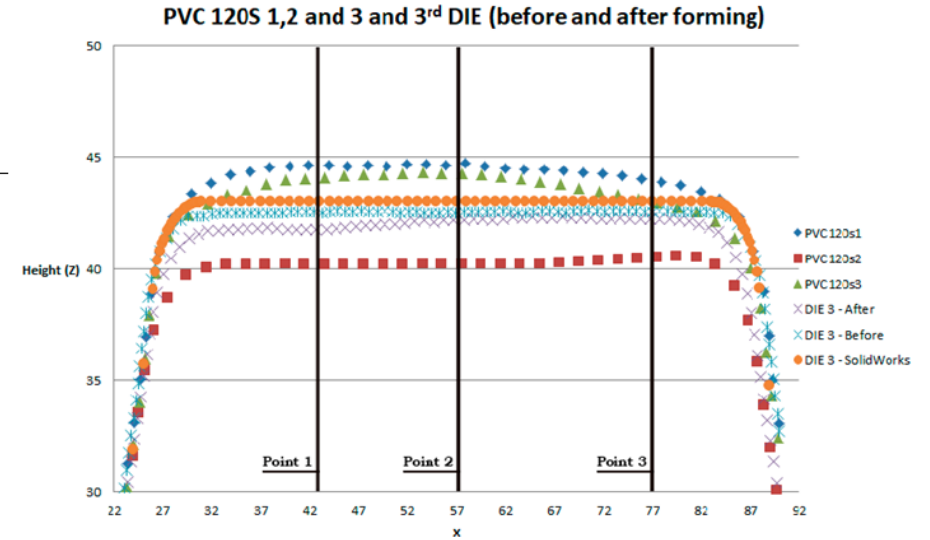
	Original (x)	Standardised (x)	Height (z)
PVC120s1	104,40893	41,90893	44,61784
PVC120s2	104,0005	41,5005	40,16003
PVC120s3	104,04026	41,54026	44,01129
DIE 3 - Before	104,94184	42,44184	42,53352
DIE 3 - After	105,19691	42,69691	41,72106
DIE 3 - SolidWorks	47	42	43

	PVC120s1	PVC120s2	PVC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC120s1		4,45781	0,60655	2,08432	2,89678	1,61784
PVC120s2	-4,45781		-3,85126	-2,37349	-1,56103	-2,83997
PVC120s3	-0,60655	3,85126		1,47777	2,29023	1,01129
DIE 3 - Before	-2,08432	2,37349	-1,47777		0,81246	-0,46648
DIE 3 - After	-2,89678	1,56103	-2,29023	-0,81246		-1,27894
DIE 3 - SolidWorks	-1,61784	2,83997	-1,01129	0,46648	1,27894	

**Point 2**

	Original (x)	Standardised (x)	Height (z)
PVC120s1	120,42132	57,92132	44,70044
PVC120s2	120,01039	57,51039	40,20652
PVC120s3	120,04234	57,54234	44,26018
DIE 3 - Before	119,4074	56,9074	42,5073
DIE 3 - After	120,21615	57,71615	42,18842
DIE 3 - SolidWorks	62	57	43

	PVC120s1	PVC120s2	PVC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC120s1		4,49392	0,44026	2,19314	2,51202	1,70044
PVC120s2	-4,49392		-4,05366	-2,30078	-1,9819	-2,79348
PVC120s3	-0,44026	4,05366		1,75288	2,07176	1,26018
DIE 3 - Before	-2,19314	2,30078	-1,75288		0,31888	-0,4927
DIE 3 - After	-2,51202	1,9819	-2,07176	-0,31888		-0,81158
DIE 3 - SolidWorks	-1,70044	2,79348	-1,26018	0,4927	0,81158	



**Point 3**

	Original (x)	Standardised (x)	Height (z)
PVC120s1	140,43517	77,93517	43,85738
PVC120s2	140,00362	77,50362	40,49429
PVC120s3	140,0275	77,5275	42,97325
DIE 3 - Before	140,2766	77,7766	42,58749
DIE 3 - After	140,26958	77,76958	42,2092
DIE 3 - SolidWorks	82	77	43

	PVC120s1	PVC120s2	PVC120s3	DIE 3 - Before	DIE 3 - After	DIE 3 - SolidWorks
PVC120s1		3,36309	0,88413	1,26989	1,64818	0,85738
PVC120s2	-3,36309		-2,47896	-2,0932	-1,71491	-2,50571
PVC120s3	-0,88413	2,47896		0,38576	0,76405	-0,02675
DIE 3 - Before	-1,26989	2,0932	-0,38576		0,37829	-0,41251
DIE 3 - After	-1,64818	1,71491	-0,76405	-0,37829		-0,7908
DIE 3 - SolidWorks	-0,85738	2,50571	0,02675	0,41251	0,7908	

Illustration 57.- PVC120S + DIE3 comparison

## Annex VI – Manual document to scan bodies

### VI.1. Introduction - Aim of the document

This document presents a practical guide to use the 3D scan, and how to scan a desired object using SHINING3D hardware and software, and then to treat the created meshed body in Geomagic to compare two 3D scanned bodies in SolidWorks.

For general and/or extra information about the scan, please refer to the software manuals:

Quick guide:

<https://www.einscan.com/wp-content/uploads/2020/05/EinScan-Pro-2X-Plus-Quick-Guide-1112.pdf>

User manual, for software version V3.3.0.2

<https://it3d.com/wp-content/uploads/download-files/manual/en/EXScan-Pro-User-Manual-V3.3.0.2.pdf>

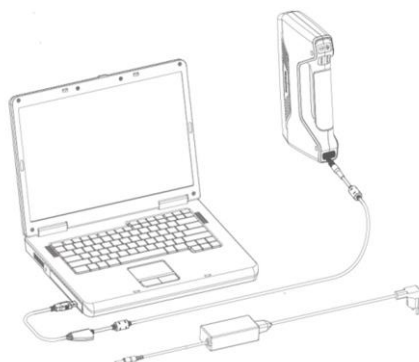
This document also includes the methodology to import data profiles from the CMM Machine (.txt file) to Solidworks, and how to compare those data with the 3D scanned bodies.

If you need information about the CMM Machine usage, please refer to the document named “Mitutoyo - User Manual”.

### VI.2. Scan setup

Following, the steps needed to be performed in order to use the scan and obtain the 3D models correctly.

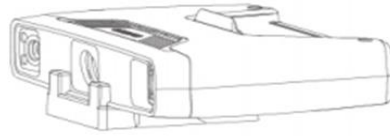
1.- Firstly, the power supply should be connected, one side to the power outlet and the other one to the USB cable. Then, the scan to the computer via the USB cable, as it follows:



2a.- If a hand-held scan is wanted (not recommended), go to step 3.

2b.- If a fixed scan is wanted, with the turntable (recommended), the “Industrial pack” needs to be installed/mounted.

2b.1.- Firstly, place the scan to its support:



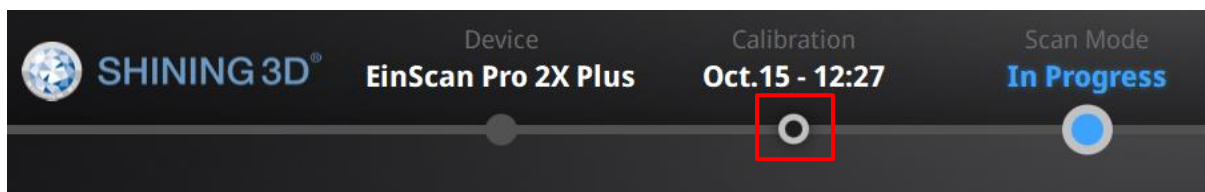
2b.2.- Then, prepare the turntable, with the power supply connected to the power outlet and the tripod placed as it follows. Also, remember to connect the turntable to the computer via USB. The whole connection should look like the image below.



3.- Once the setup process is done, regardless of it being handheld or fixed, it is now needed to calibrate the 3D scan, if it has not been done recently. Once every two weeks is recommended.

### VI.3. Scan calibration

In order to calibrate the scan correctly, the software needs to be opened. Then, press the Calibration option (black dot).

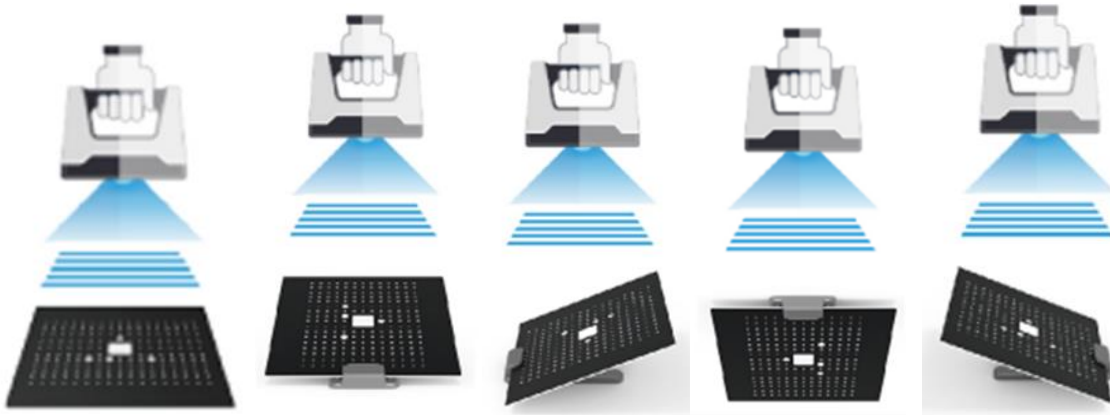


There are two different calibration methods. Usually, the normal calibration should be performed. The “accuracy calibration” option will only be needed after a few months, in case the scan is not working correctly.

The methodology used are the next five steps. Even though the software does already give you a Step-by-step representation and explanation, here it is defined as well.

The whole process is performed with the scan being handheld, without a tripod.

Place the table calibration touching a plane surface, with the white dots looking at the scan. Then, place the scanner looking towards the table calibration, and move it up and down vertically, depending on the software specifications. Following, use the calibration support to place the table calibration into its place, and repeat the same procedure every 90°. Following, there is a diagram with the 5 different table calibration positions.



#### VI.4. 3D SCANNING and 3DShining

1. Previous to scanning the body.

The hardware to use is the following:

- EINSKAN PRO 2X PLUS mounted on a tripod structure
- Turning plate to place and position the body.

Once the SHINING 3D software is running, and before scanning, the SCAN has to be calibrated, if it is not already done.

Screen 1:



The “Fixed Scan” on “Scan mode” has to be chosen. Then, select New Work or Open Work, and select a Folder for the scan.



## Screen 2:

Select “Non-texture scan” and Apply to start working with the scan.

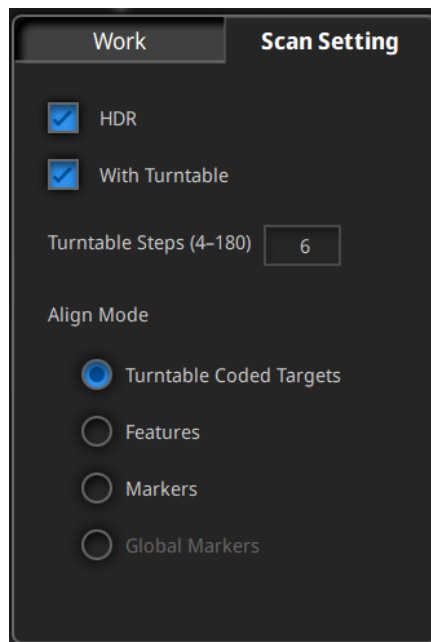
At this point, the scan should have opened and a blue surface should be seen. If the scan is not projecting a blue surface, check the scan’s connection and behind the scan to make sure it is operating, then close and reopen the program.

Once we are ready to scan, it must be started by placing the body on the plate, centering the scan vision to the turning plate.

Then, the scanning process can be started.

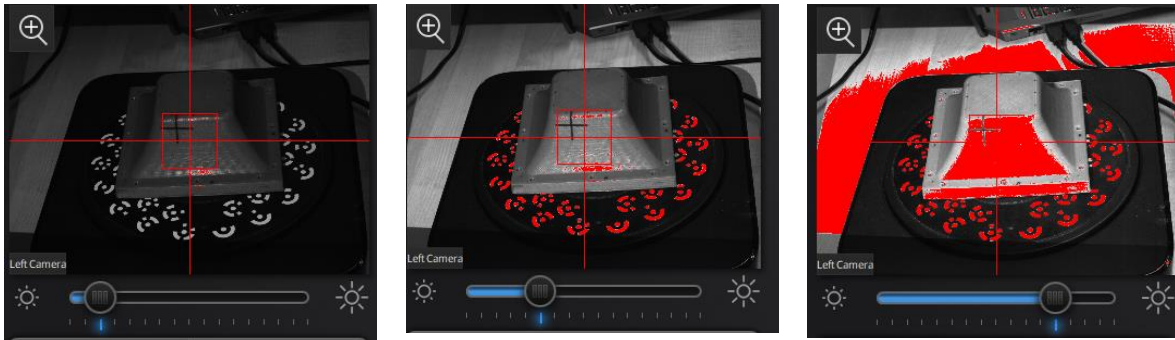
## VI.5. Body scanning

The scan setting panel will look like the following picture, and the main points to take into account are: HDR, Turntable Steps and Align Mode.



### HDR and correct focus

Firstly, the correct light focus should be given to the body. The HDR marker should be unselected and then search for the best focus, by dragging the button, and the result should be as the following images:



Under focus (too little light)

Correct focus (right light)

Over focus (too much light)

In resumé, it must be searched to have the white marks of the Turning Table in red but not the surface of the body. Once the scanning light is correctly focused, the HDR setting should be reactivated for higher resolution.

### Turntable steps

Now, the steps from the turning table must be determined. The turning steps determine how many scans are done in a 360° view. From a range of 4 to 180, select the steps you will need to see the body correctly. It is recommended to choose the lowest value possible, since a bigger one may increase the positioning error between them.

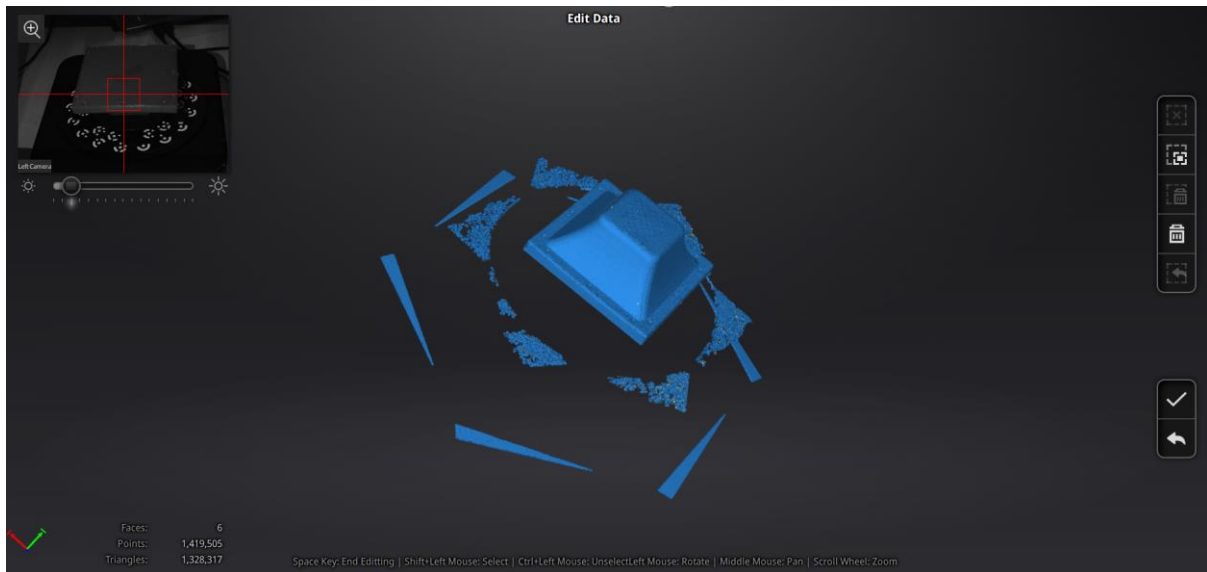
### Align mode

Align mode refers to the reference used by the scan to diagnose and analyze the body. It can be chosen between three different options:

- **Turntable coded markers:** In this mode, the scanner uses the white markers which appear in the turntable to localize the body.
- **Features:** The scanner searches for the body shape without extra markers or points.
- **Markers:** In this mode, rounded black and white markers (stickers) have to be positioned around the body. The markers .STEP file should have been defined so that the scan can find them.

To choose the right align mode is extremely important because if chosen wrong, the scan won't trigger and scan photos will not be taken. Therefore, the following pathing is preferred: Firstly try with turntable coded markers, try not to cover all of them or none if the body geometry allows it. Then, try the features scan, without covering the white coded markers and try then by covering them. By that time, you will have already seen that the white surfaces are easily found by the scan. If the scan is still unable to see the body, it is preferred to either use a white spray can for scanning, following its instructions, or use the stickers.

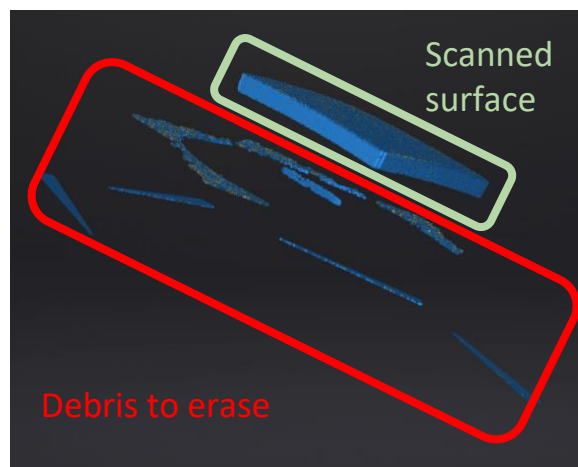
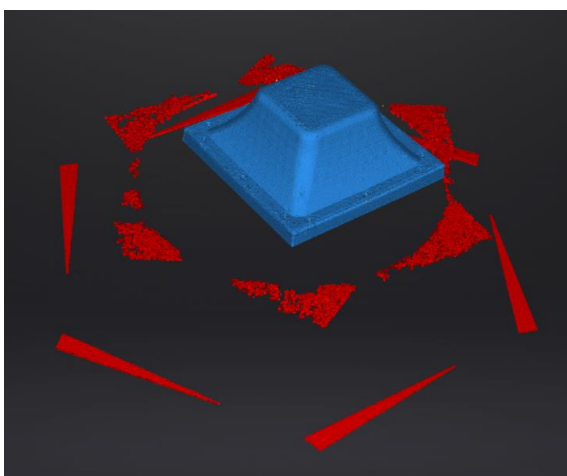
After the body has been scanned, you may have a surface such as the following image:



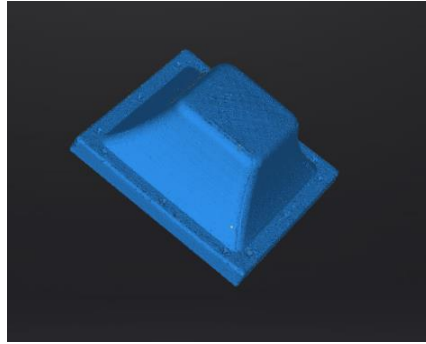
If you can correctly see the surface means that the number of turntable steps, HDR+ vision and other values have been correctly chosen. As well, it may happen that the body does have a color which is not possible to detect correctly by the 3D Scan. In those cases, you may need to spray the body or use external lighting in order to make sure that the scan can see the body correctly and differ between the body and the turntable.

Following, you will need to trim the extra surface which the scan does create. It is just needed to select the external surfaces / debris and delete them. Depending on the body, it may be more difficult. In those cases, use the mouse to 3D rotate the body and you will see that the debris will be shown in another plane, making it easier to select (as shown following) and, thus, delete.

In order to select the debris, just use the command “Shift + Left mouse button” to select the zone. (you will notice the possible commands shortcut next to the number of faces and triangles, at the center-bottom of the screen)

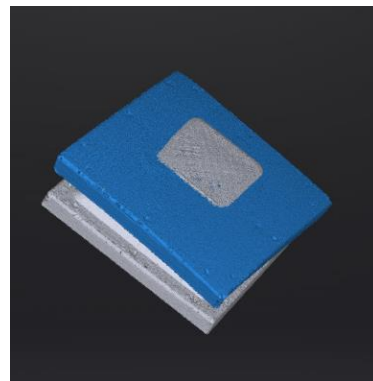
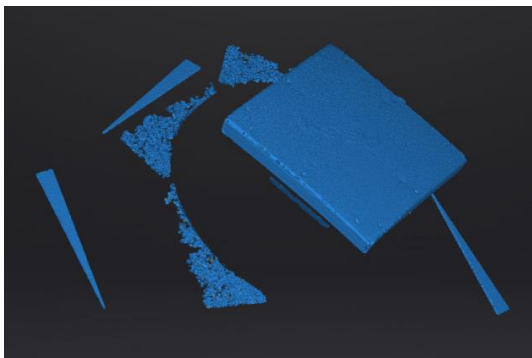


Once the debris has been trimmed, your body should look like the image below:



In this case, you will already have done the first part of the scan. Now, it is left to close the body by scanning the part of the body which was touching the build plate. Therefore, you need to reposition the scanning body, and start a new scan, by pressing the “Play” button on the right side of the screen.

The result must be the same as the first scan. Notice that firstly, you will only have the new scan and the previous one will have disappeared. Once you trim the debris and accept the edit, it will appear, as shown following:

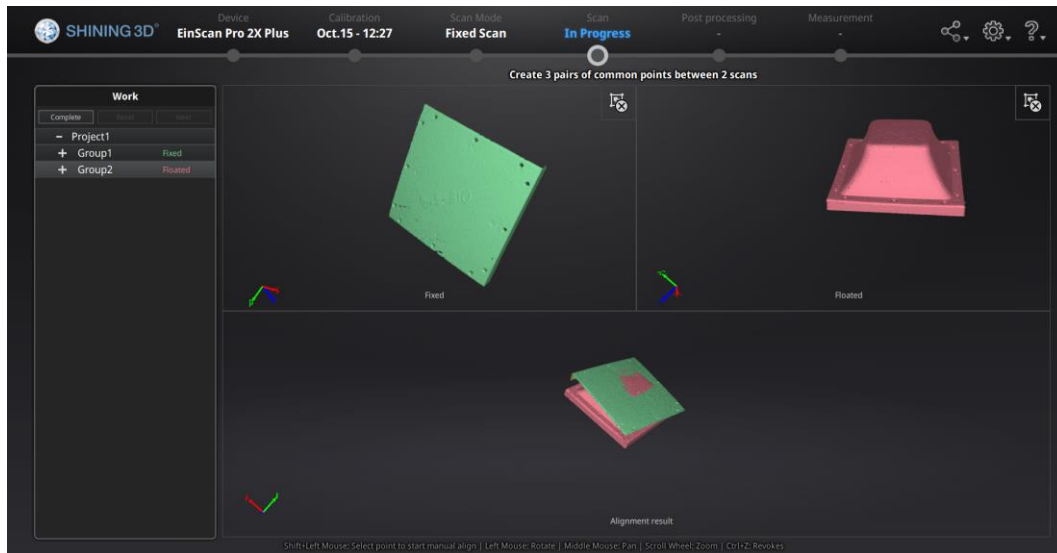


As you can see, both scans have been performed correctly but one is overlapping the other. Now, it is needed to select “Alignment mode”, in order to position the different scans.



Do another scan

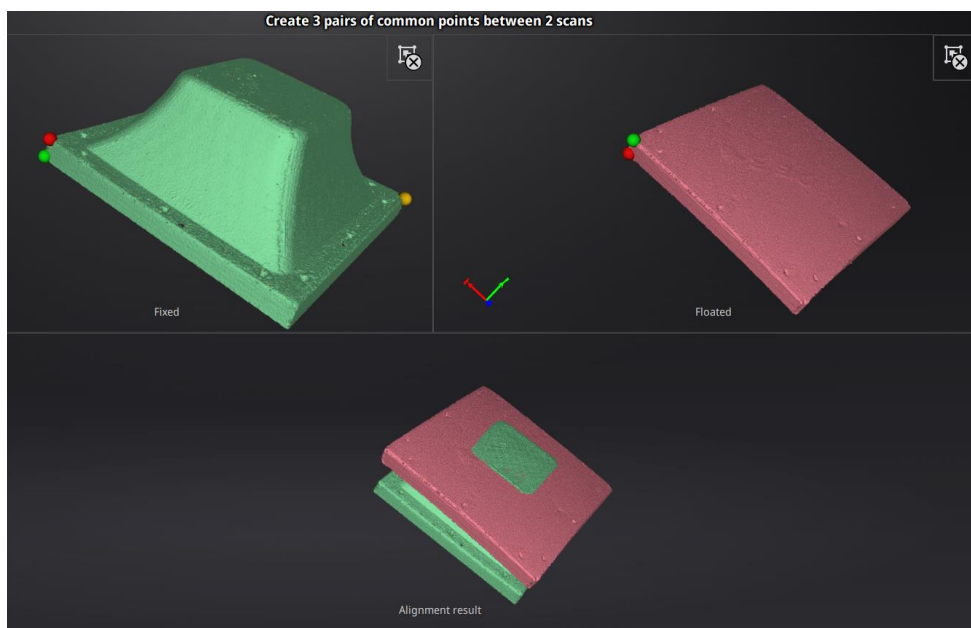
Go to alignment mode



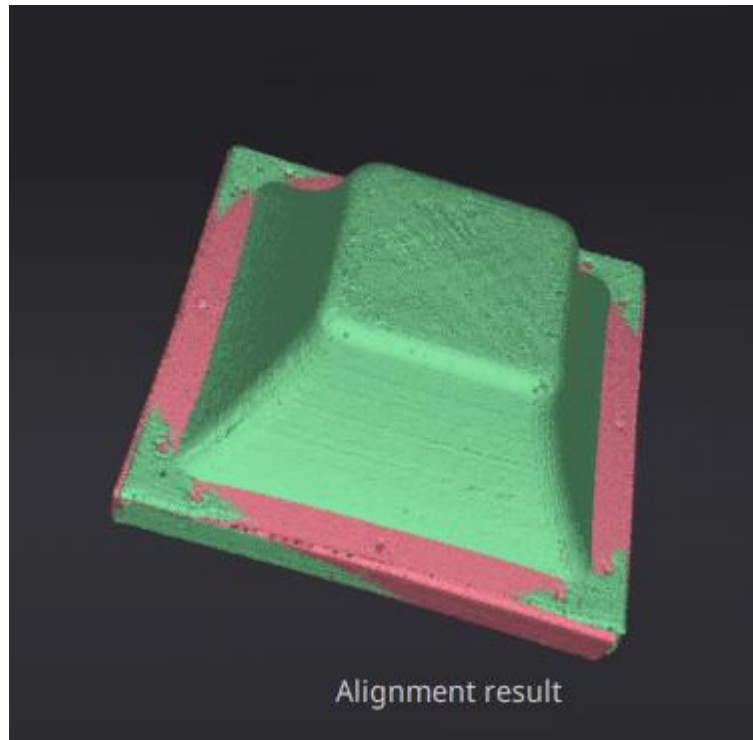
You will notice that each scan has been divided into a different Group. “Group 1” represents the first scan, and it is composed of all the different photos taken by the scan (number of turntable steps chosen).

Now, it is needed to select one group for each panel, having one scan on the left-side of the alignment mode, and the other one on the right.

Then, it is just needed to create 3 pairs of common points, by using the command “Shift+Left Mouse”, you will select one point in one scan, and then go to the other one and select the exact same point, so that the software understands the geometry of it, as if you were defining the same (0,0) reference point.



Repeat the same process for each pair of points, and following you do have two pictures showing both the common points process and the alignment result.



Once the alignment result has been generated, you can either accept or reject the result of the alignment and either continue the process or repeat these last steps.

After the alignment process, save the progress and then click on “Mesh body” to create the .stl file.



You will then have the possibility to choose between “Watertight model” or “Unwatertight model”. Choose unwatered since this body has already been closed.

This feature is used in case that you have not closed the body (e.g. not done the scan for the surface touching the build plate) and then it auto generates a surface to close the body, following the geometry already taken. Unfortunately, after many tryouts it has been determined that this automatic process mostly leads to an enormous amount of errors and does not correspond to the real shape of the body.

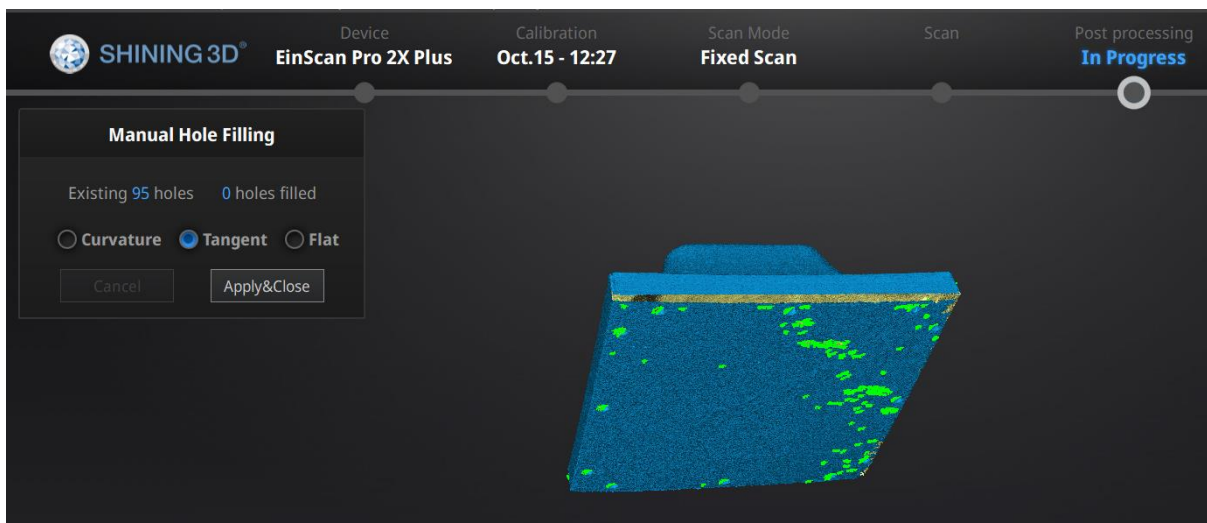
## VI.6. Post processing:

Right after having the model closed and the mesh has been created, it is time to post-process the scan and generate the body according to the specifications required.

The post-processing does comprehend different softwares, briefly described as it follows:

- SHINING 3D
- Geomagic Essentials
- SolidWorks.

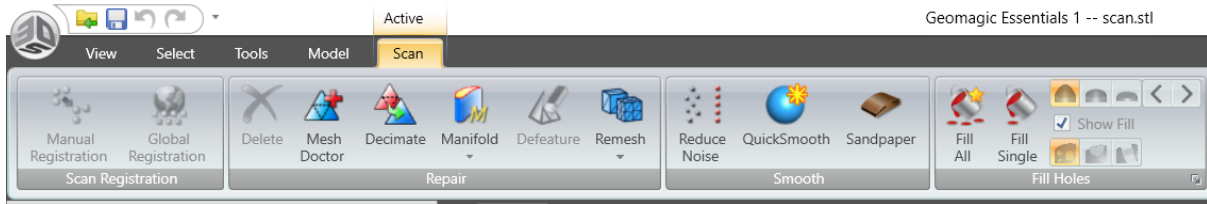
The first step, which can be done in either SHINING 3D or Geomagic, is used to close small holes which have been generated either directly from the scanning process or as a result from meshing the body. Once it is done, it is needed to use the “Third-party software” button, on the right side panel of the screen, in order to open the file in Geomagic.



The body will automatically open in Geomagic Essentials.

## Geomagic Essentials

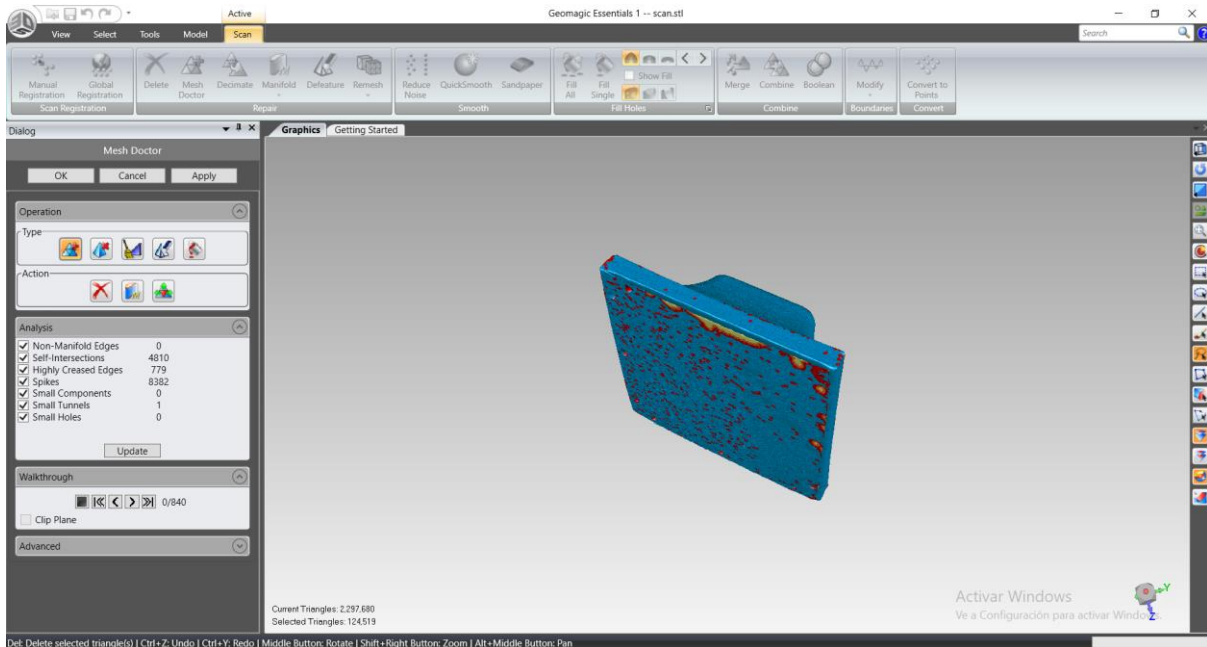
Once it has been done, the same software will ask to use the “Mesh Doctor”.



Since Geomagic Essentials is a software especially designed and developed for mesh analysis and configuration, the Meshing Doctor detects the defects in the mesh automatically and gives you the opportunity to automatically fix the selected problems. Following, it can be seen the detects encountered in red and yellow, being either Small Holes, Spikes, Small Tunnels, Self Intersections, between others.

As an example, in this case it has been found +10,000 errors in a +1.7 million triangled-mesh surface.

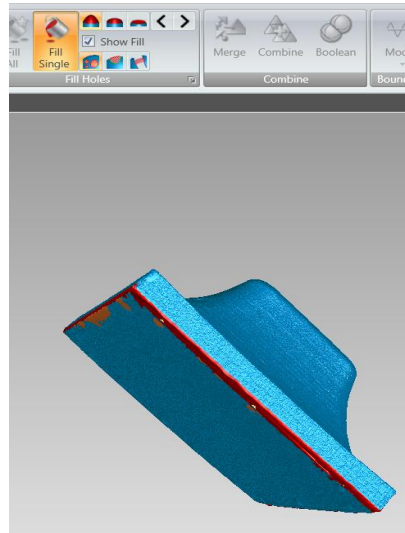
Depending on the needs for the mesh body, those recommendations will be applied or dismissed. It is recommended to, at least, apply the recommended changes for Small Tunnels and Small Holes, as well as the Self Intersections, if it is supposed to be a fully closed body.



In cases where there are some holes which are part of the body scanned and should not be closed, it is possible to either use the tool “Manual hole filling / Fill triangle”, which will allow to both fill the holes which you can determine as errors and leave the ones from the geometry open. Or also use the SHINING 3D software option which does allow you to select a measure, (ex.0,2mm) and then it only closes the holes which are smaller than those values.



As well, if the body has not been perfectly closed after aligning the bodies, due to imperfections in either meshing the body or scanning it, it is possible to fully close the body in Geomagic Essentials, using an infill tool, the “Fill triangle”. It does not only allow to close small holes but also to fill small open surfaces, while allowing to choose the geometry of the closing structure (curved, plain or inverting-curved from each side of the hole)

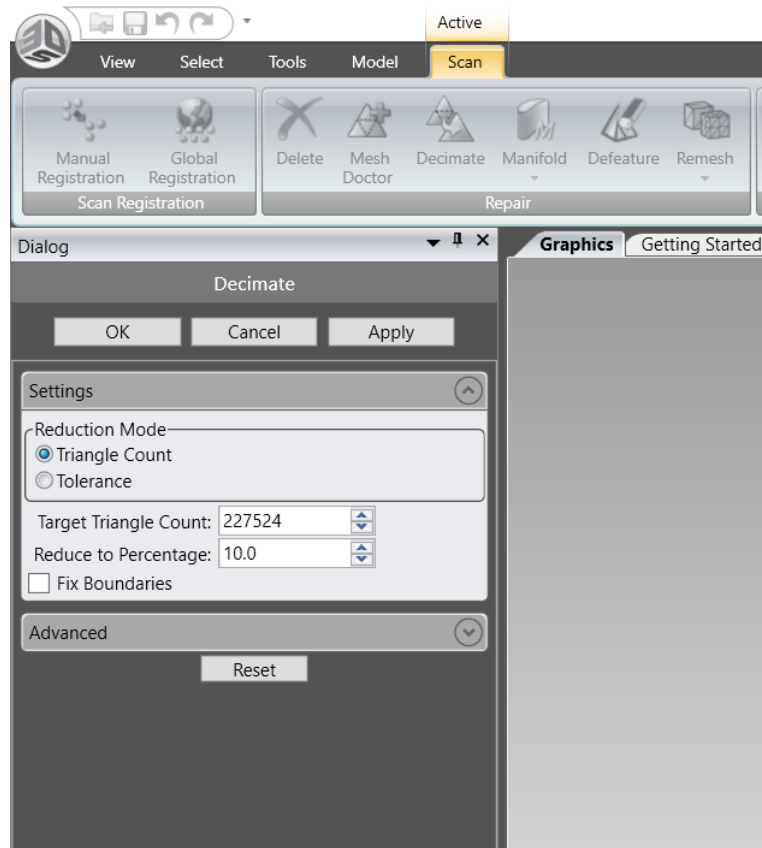


Given the high resolution of the scan, the meshed body will be generated by millions of triangles. Taking the shape of the study body of this manual, this body does contain more than one million triangles for each scan.

Therefore, the body you may be working with will also have a huge amount of detail. Because of that, it may lead to not only a heavy file. Because of that, it is recommended to use the “Triangle reduction” tool, on the “Decimate” section, since it will lighter the file but unfortunately it may lead to a lower resolution of the body.

Note. Even though it may lead to a lower resolution of the body, we are talking about a body which does have a really high resolution. To put into perspective. If you do write into a body which will later on be scanned, the initial resolution does have the capability to find the height created when writing, and once it has been “decimated”, the mesh resolution does still have the capability to determine the expression written with high resolution. Therefore, since the Solidworks does have problems to open bodies with over 10 thousand triangles (2021 version) with a normal computer processor, to decimate the body does allow to open the body and compare it later on without having to wait 10-15 minutes for opening the file without losing resolution, a efectos práctics.

Following, an example of the panel to decimate the meshed body.



Once the previous steps have been performed, the progress should be saved as an .stl file and then opened in SolidWorks.

## Annex VII – Manual document to compare bodies

### VII.1. Introduction - Aim of the document

This document presents a practical guide to compare two bodies, being at least one a .STL file, from a scanning process for example.

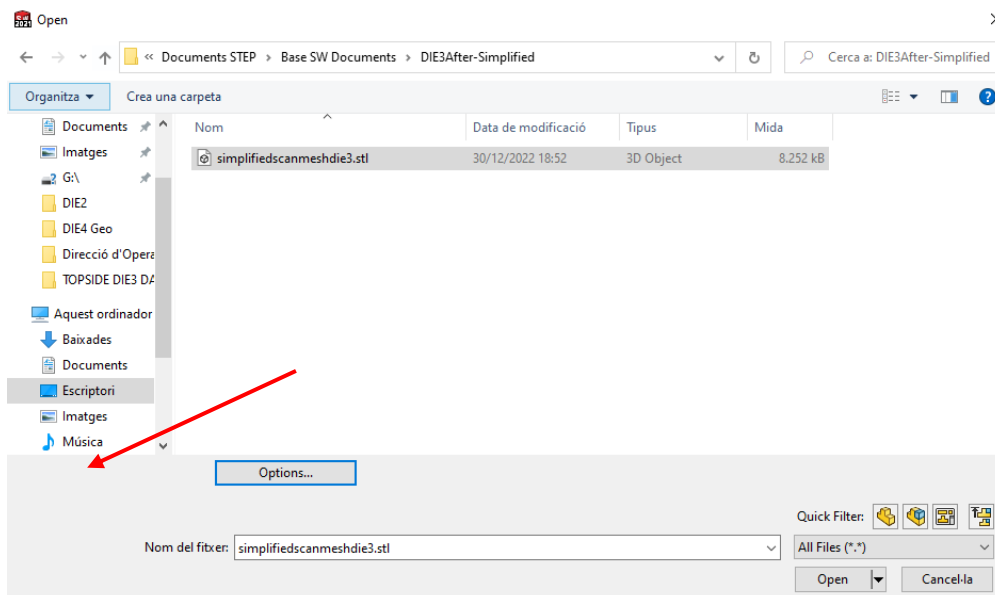
This methodology allows to compare the following combinations of bodies, comparison between:

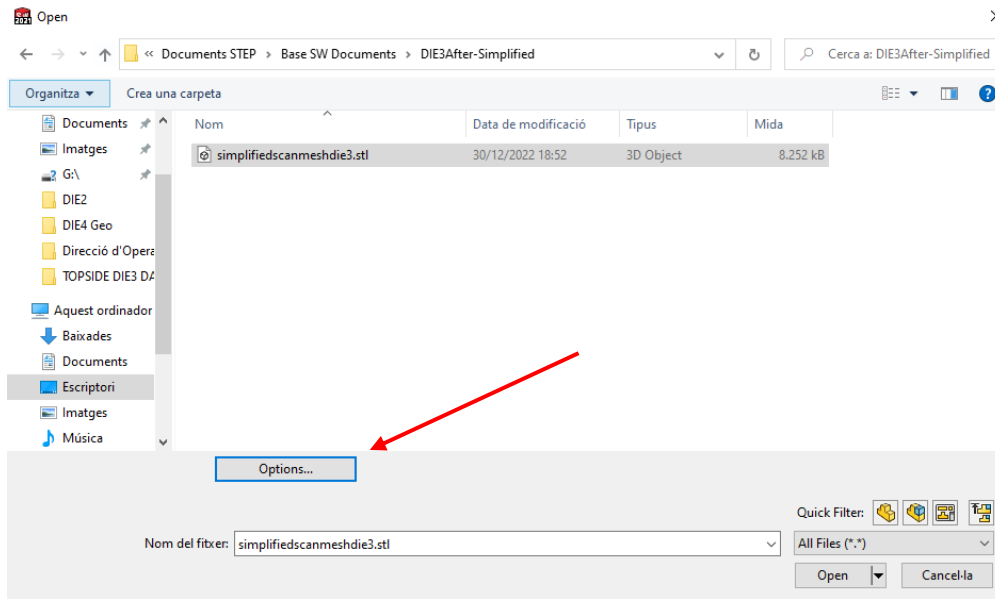
- Two SolidWorks designed bodies,
- One SolidWorks designed body and one .STL file,
- Two .STL files.

### VII.2. SolidWorks - Body comparison

If you are working with two Solidworks designed bodies, then you can go straight to “Referenced comparison”

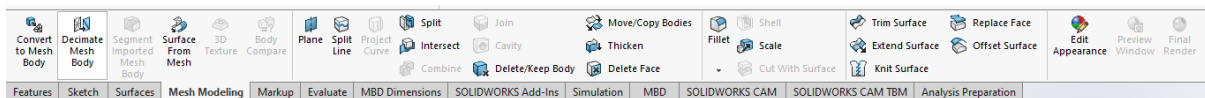
When working with .STL files, it is important to select the correct Options before opening it. Therefore, the following options have been defined as the best way to open the file and also allows to open the body correctly, since other options will ultimately lead to the same result but with higher time response from SolidWorks and your computer.





Be patient since it may take some time, depending on your computer’s processor, and the amount of “facets” or triangles that your .STL file mesh does have. Once it has opened correctly, it will automatically be renamed as an .SLDPRT file, and it can then be saved as a .SLDPRT, to ensure a quick opening next time.

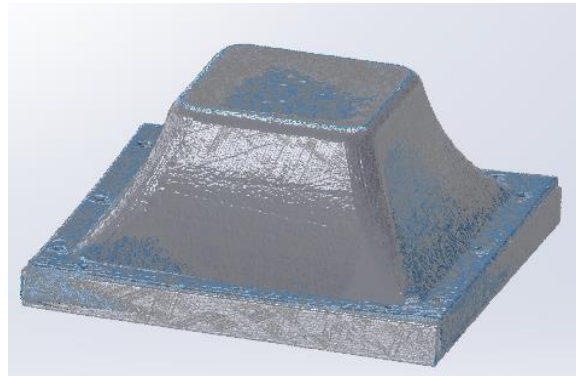
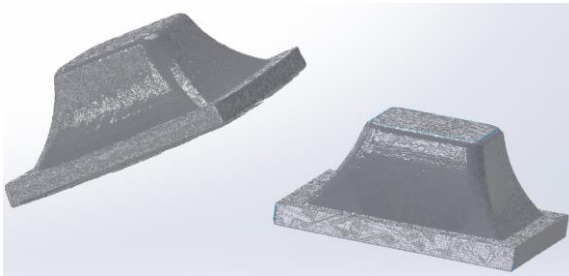
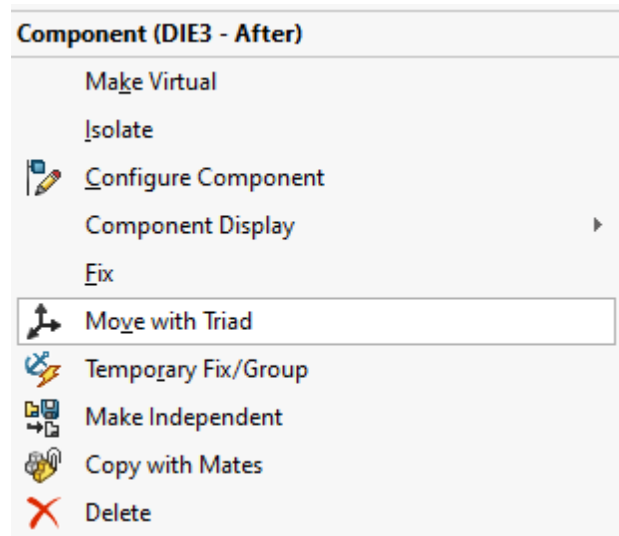
Now, it is possible to start working with this file as a mesh body in order to do some Inverse Engineering. The main tools are located in the Mesh Modelling section, as follows:



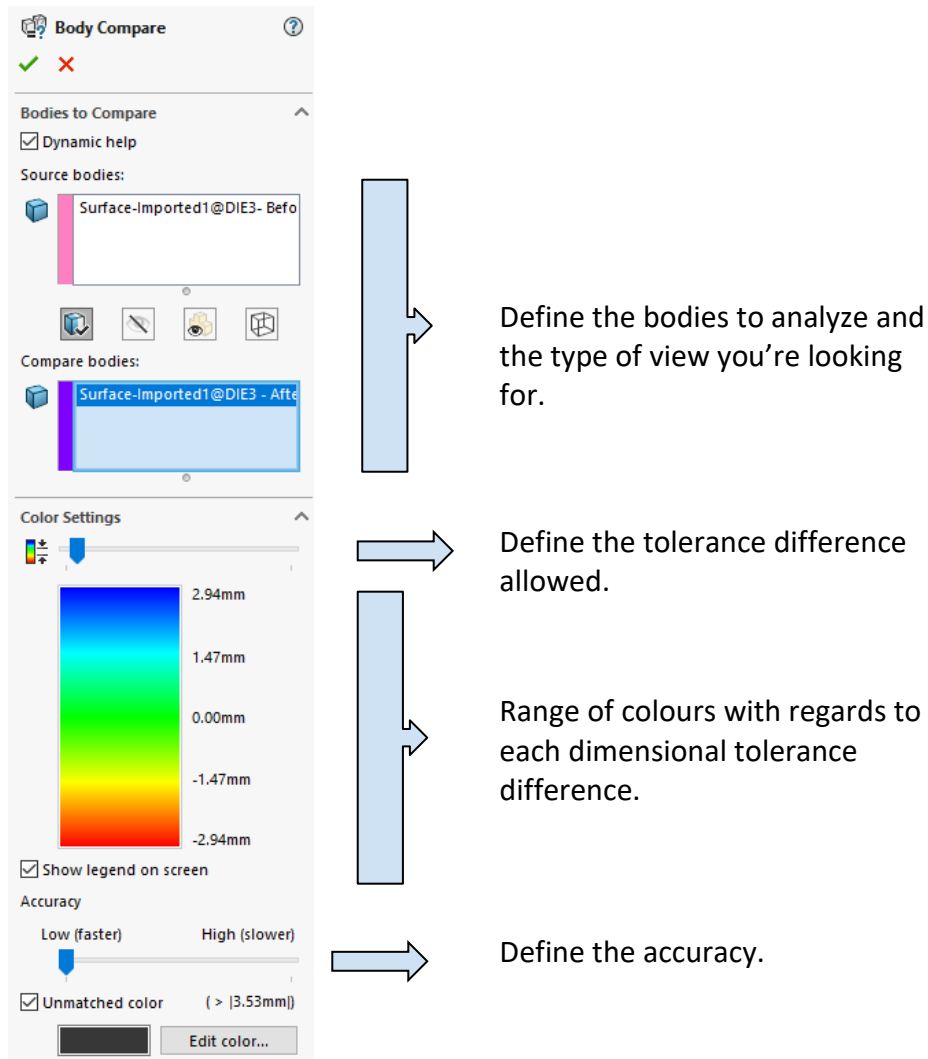
As one example of it, this document will now focus on comparing two .SLDPRT files, when at least one is a scanned body.

### VII.3. Approximative Comparison

In order to compare two bodies, it is needed to create an assembly, so that both bodies are in the same workspace. Once it has been created, both bodies should be uploaded to the assembly itself, in order to compare them. Then, use the Triad tool to move the second body and align it with the base body, so that you can compare one over the other. To use the “Triad” tool, right click on the body you want to move, and select “Move with triad”.



Once they are completely overlapped or right on the desired position to compare, the comparison tool “Body compare” should be clicked and then defined.



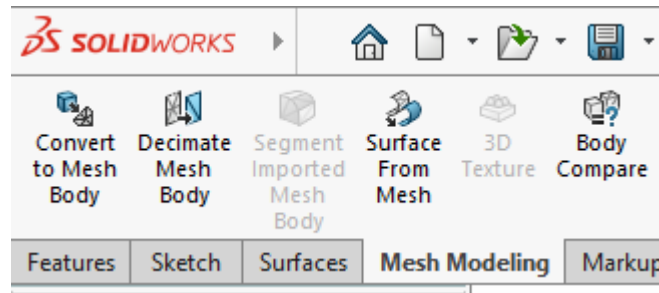
If the tolerance given by the Triad tool is not exactly what your system is looking for and you need to implement exact points to compare geometries from, then the analysis pathing is quite different, and is defined below, in “Referenced Comparison”.

#### VII.4. Referenced Comparison

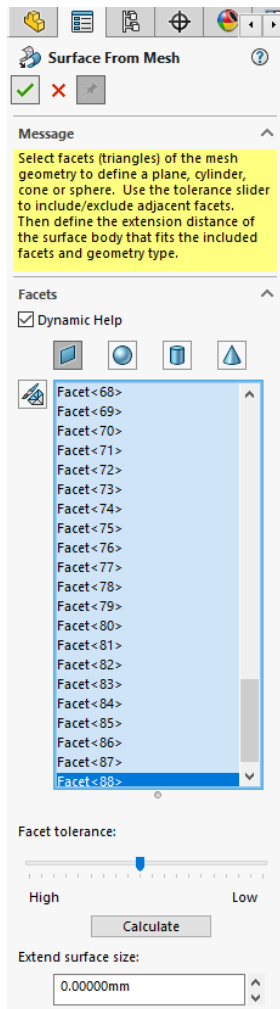
In this case, there are some steps that need to be performed to each .STL file before going straight to create an assembly.

Therefore, once you have the .STL file opened, you need to use the “Mesh modeling” options in order to create and define the geometry references to correctly overlap the bodies.

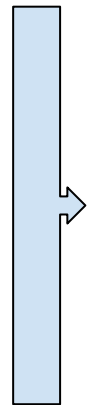
For each scan body, you need to use the tool “Surface from Mesh”.



This tool allows you to select the desired triangles which take part from a specific geometry, such as a plane or a cylinder, and then the software will join them as if it was a Solidworks created plane surface. Use this tool to create planes, and then points, to reference the bodies you are analyzing so that you can then compare both bodies, using the same exact vertices, plane surfaces and points you have just created.



Define the geometry of the surface.



Number of facets/triangles chosen to take part in the same surface to be defined.

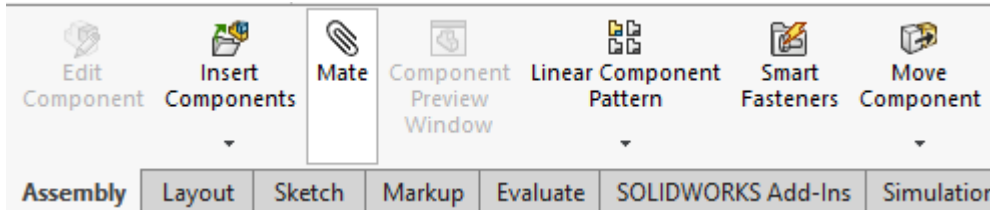


Define the tolerance difference allowed. ( a lower one means only the facets which do have the same orientation will work- better but more difficult)

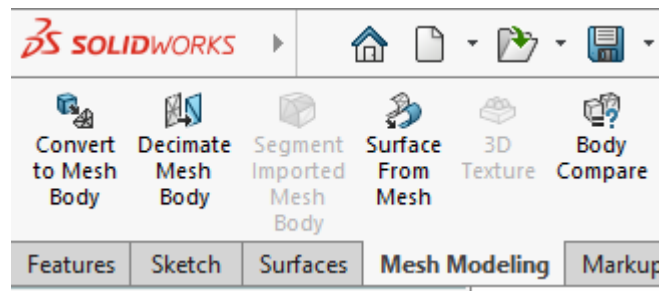
Play with the amount of triangles chosen, as well as the facet tolerance, since you will see that many times it won't work with random triangles. As a tip, try to choose the perimeter triangles, as well as some in the middle, and lower the tolerance. Then, try to "High" the tolerance and the amount of facets (triangles) as much as possible since it will give you a more accurate surface with respect to the body.

Once you have done it for each body, then create an assembly, and right after implementing the two bodies in it, use the “Mate” tool to create relations between different bodies.

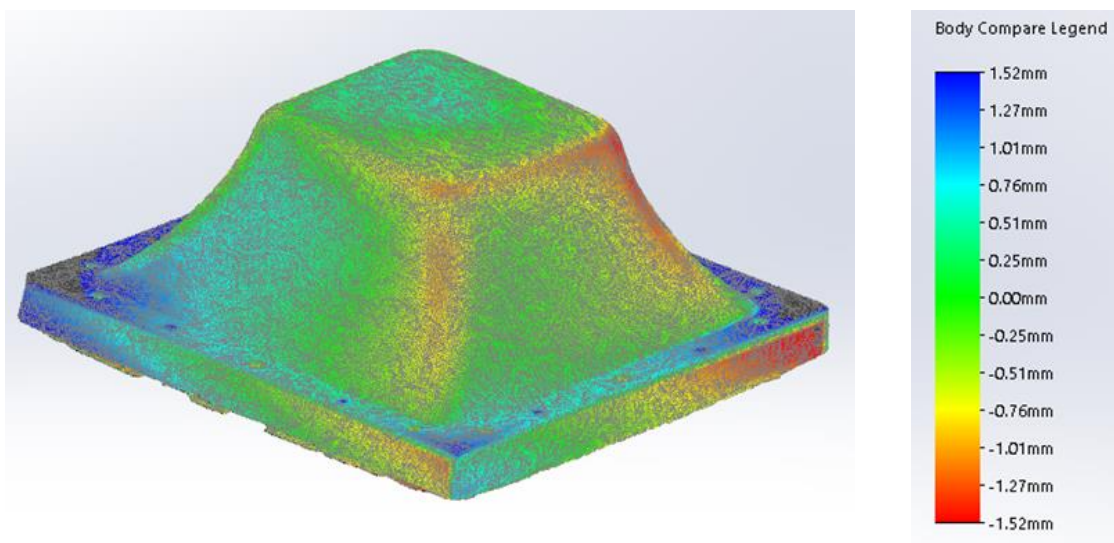
**Note.** If you are comparing one .STL file and one solidworks designed body, you don’t need to create the references for the solidworks body, only for the .STL file, since you will be able to select each and every exact point that you want, the “Mesh modelling” tools do work with .STL files with undefined surfaces.



Use this tool to select the desired point, plane or reference from which you need to compare the bodies and have already defined before, and they will already be perfectly aligned. Then, you will be able to compare both bodies. In order to do so, use the “Body Compare” tool as specified in “Approximative Comparison” method.



The final result may look like the following images:





## Annex VIII – Budgeting

*Table 27.- Project budget.*

Description	Units	Price	Total (€)
<b>ENGINEERING WORK</b>			
<b>Direct expenses</b>			
PVC sheets cost	9	1.06€/each	9.54
PC sheets cost	9	0.76€/each	6.84
PLA	31 gr	25€/kg	0.775
<b>Personnel expenses</b>			
Literature research	12h	15€/h	180
Machinery usage	20h	30€/h	600
Data treatment and protocol tryouts implementation	100h	30€/h	3000
Report elaboration	45h	30€/h	1350
<b>Management expenses</b>			
Meetings	5	70 €	350
<b>Administrative expenses</b>			
Communications	1	20 €	20
<b>Subtotal</b>			<b>5523.99</b>
<b>OPERATING EXPENSES</b>			
<b>IT licenses</b>			
Microsoft office license	1	69 €	69
Geomagic license	1	6.900 €	6900
EinScan-Pro (Hardware + Software)	1	4.099 €	4099
Solidworks license (Student version)	1	0 €	0
<b>Subtotal</b>			<b>11068</b>
Total VAT free		16.591,99 €	
V.A.T 21%		3.484,32 €	
<b>Total budgeting</b>			<b>20.076,31 €</b>