Integrating Metal 3D Printing & Flexible Post Processing

Output O3.1 Development of process and manufacture of prototype tool

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1.0	21/10/2018	Draft issue.
1.1	05/04/2019	Added 3D&FPP Layout, first review
2.0	18/07/2019	Processed remarks by project partners

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1 INTRODUCTION

1.1 OUTPUT DOCUMENT 3

The key deliverable of Output 3 was a prototype demonstration, which has been summarised and captured in this Output Document.

According to the Application Form (AF), output 3 includes the development of procedure and tool (compiler), whereby a prototype for the tool and the procedure of post processing is developed as a stand-alone version after WP2. This output should confirm the development of TRL 6 (technology demonstrated in industrially relevant environment).

Each chapter of this Output Document O3 will discuss in detail all research activities taken by the respective Project Partners. As well as their research results. In this Output Document O3, the progress of the project 3D&FPP will be evaluated on two aspects: Introduction Costs and Introduction Time saving (section 1.2) and Technical Feasibility (section 1.3). Both aspects will subsequently be addressed in O.4 and be concluded in O.5.

The overall planning for O.3, O.4 and O.5 is given in section 1.4.

This document discusses the activities of Workpackage 2: the development of a prototype based on existing technologies.
These activities are divided in two phases:

1. Process description and
2. Tool development.

1.2 COST AND TIME SAVINGS (TO BE CONCLUDED IN O.5)

It is a generally accepted that the costs of subtractive manufacturing (whereby material is milled away to obtain the final part) are substantially lower than additive manufacturing (AM, whereby parts are built by addition of layers). With the AM process it is possible to manufacture one-off's, complex structures and on location, on demand. On top of that AM enables manufacturing of weight optimised structures without any additional costs. These structures would generally be impossible to manufacture using subtractive manufacturing.

The AM process is therefore not directly comparable to subtractive manufacturing. The 3D&FPP project will therefore focus on reduction of post processing costs through increased yield and reduction of processing time. Furthermore, the calculations will be carried out on parts that are designed for AM, which therefore can only be manufactured through 3D printing, and planned to be post processed in a fully integrated post processing environment.

Each process step applied to the part will add time and cost of production. Hence, parts scrapped at the later stages of post-process will ultimately increase the production cost and time for manufacturing a batch of parts. To minimise production cost and time, it is essential to identify defects as early as possible. Keeping that in mind, the post-processing steps described in the following sections are specifically designed to create an increased yield (costs saving) and decrease the overall process time (time saving).

The demonstrator tested for Output 3 was intended to showcase a feasible generic solution of the 3D&FPP's goal to reduce costs by 30% and production time by 50%.

1.3 Technical Feasibility (to be concluded in O.5)

The objective of this chapter is to have clear understanding of the process steps, their iterations and their interdependences in order to understand the prototype demonstrator. This chapter outlines all the production and process steps which are involved in post processing 3D printed objects.

1.4 Post-Process Procedure Flowchart

3D metal printing involves various production steps – a flowchart (Figure 1) was generated to clarify the process steps of 3D printing, post-processing and their interrelationships. The flowchart consists of production steps (blue), professions involved (combined areas in various colours) and communications (dotted lines).

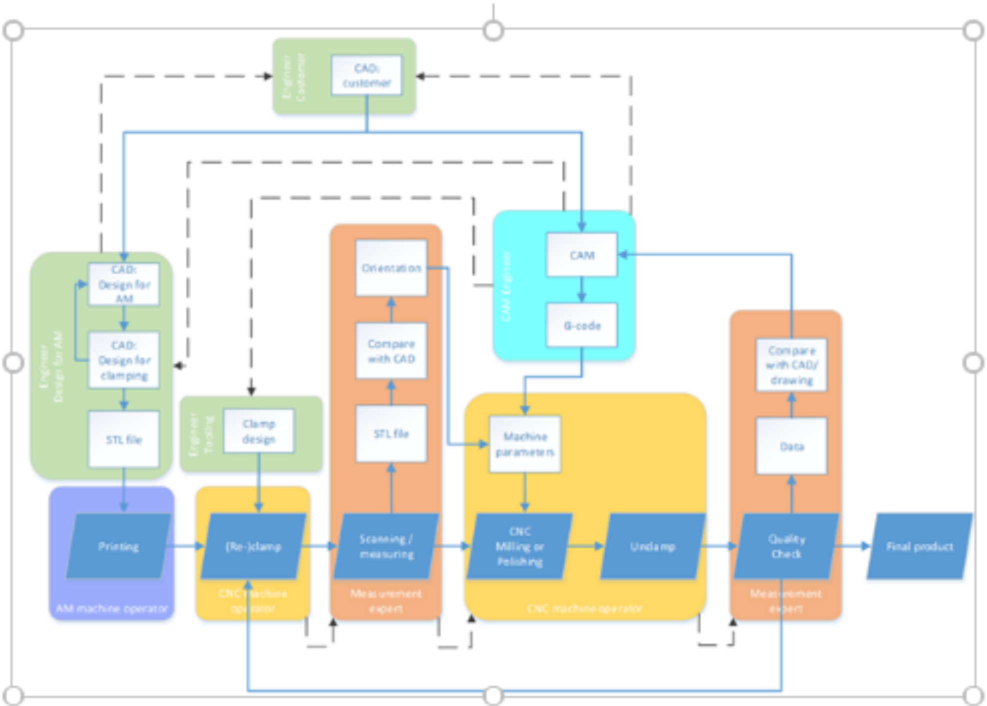

Figure 1: Post-Process Work Flow

Several iterative loops are present before the final product is finished. For instance, after the quality check a product might need to be re-clamped for additional post-processing. The same process steps apply for products that need post-processing on all sides. Another return loop is present between the “Design for AM” and “Design for clamping”.

The added value of the 3D&FPP project is its holistic or integral approach. The separate post-processing steps are considered as a whole, leading to time and cost reductions. Integration in this sense means the exchange of information between various systems rather than creating an in-line ‘post-processing machine’.

1.4.1 SYSTEM DESCRIPTION FOR PROTOTYPE DEMONSTRATOR

Based on the various production steps and the various expertise involved, the following system description and process steps can be derived and depicted (**Fout! Verwijzingsbron niet gevonden.**).

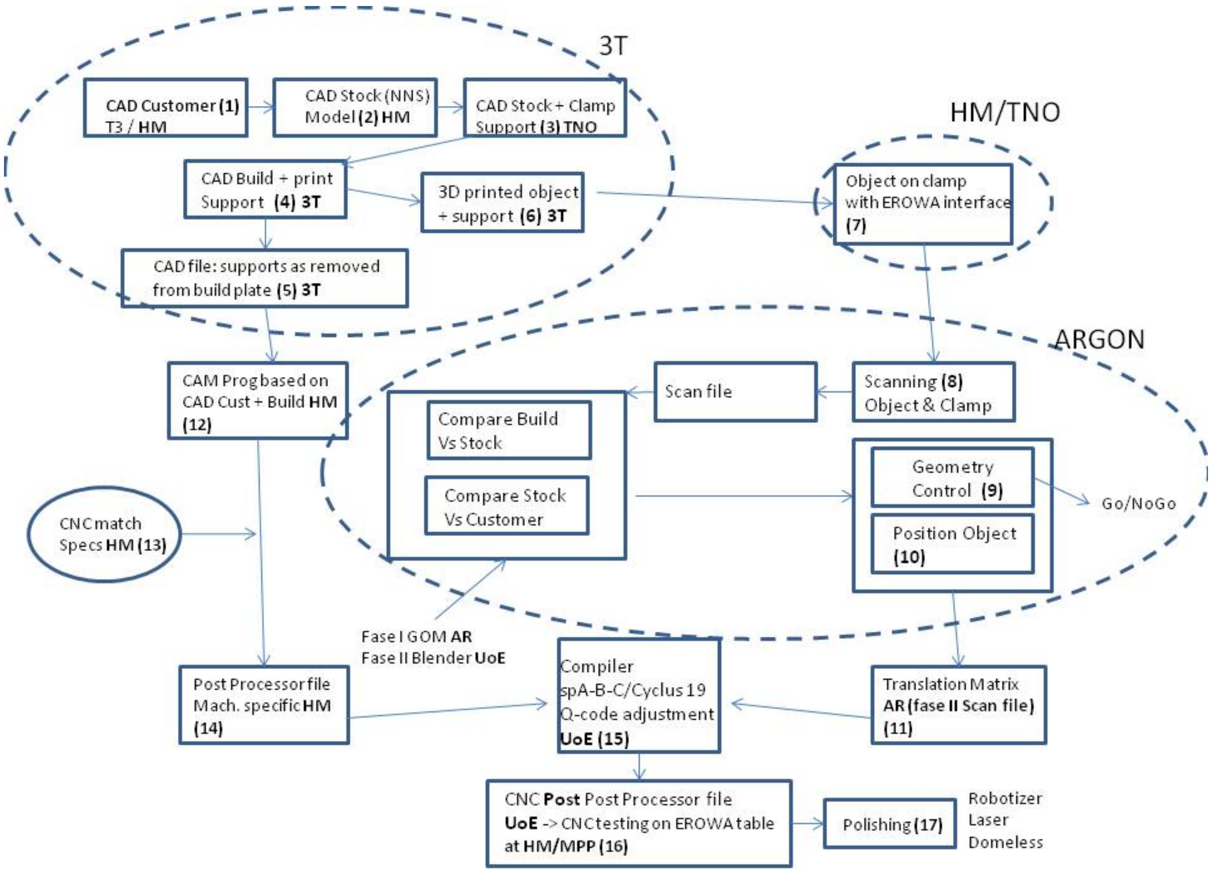

Figure 2: System Description and Process Steps Prototype Demonstrator

1. CAD Customer is the design of the object in net shape.
   Expertise involved: Customer engineer

2. CAD Stock is the CAD Customer design including an extra layer of material in order to being able to post process the surfaces of the object after being printed.
   Experts interaction involved: Customer engineer ←→CAM engineer
   Experts interaction involved: Customer engineer ←→ AM engineer

3. CAD Stock + Clamp is the design of the object in step 2 including a Clamp Support, which must be printed attached to the object.
   Experts interaction involved: Tooling engineer ←→ CAM engineer
   Experts interaction involved: Tooling engineer ←→ AM engineer

4. CAD Build is the design of the object of step 3 including its Print Support attached to the build plate. This file is used to actually 3D print the object (step 6)
   Experts interaction involved: AM engineer ←→ AM machine operator

5. This CAD file is the design of the object from step 4 as it is removed from the build plate.
   Experts interaction involved: AM engineer ←→ CAM engineer

6. Actually 3D printing the object
   Experts interaction involved: AM engineer ←→ AM machine operator

7. Mounting the 3D printed object onto a clamp with an EROWA interface.
   Expertise involved: CNC machine operator

8. Scanning the clamped object mounted on an EROWA platform.
   Experts interaction involved: CNC machine operator ←→ Measurement Expert

9. From the scan file the CAD Build and CAD Stock are subtracted. The shape left is the general geometrics of the object which can be compared with the CAD Customer (Geometry Control within tolerances, go/no-go I)
   Expertise involved: Measurement Expert

10. From the scan file the support and stock is removed and compared (best fit) with the CAD Customer. The most ideal fit determines its orientation of the CAD Customer. With this orientation in mind the CAD Customer is compared with the CAD Stock to check if there is enough stock on the respective surfaces for post processing (go/no-go II)
    Expertise involved: Measurement Expert

11. When the geometry of the object is within tolerance and there is enough stock available for post processing, the position of the object in reference to the EROWA table will be converted to a Translation Matrix
    Expertise involved: Measurement Expert

12. Based on the CAD file from step 5 a CAM file is generated.
    Expertise involved: CAM engineer

13. Determining which CNC machine will be used to generate a post processing file
    Expertise involved: CAM engineer

14. Based on the CAM file from step 11 and the CNC machine choice from step 12 a Post Processing file is generated.
    Expertise involved: CAM engineer

15. Based on the Translation Matrix from step 11 and the Post Processing file from step 14, with the use of a compiler a Post Post Processing file in generated.
    Expertise involved: Measurement Expert

16. The Post Post Processing file from step 15 is used to mill the object to net shape.
    Expertise involved: CNC machine operator

1.4.2 Cost and Time reduction due to Technical Process Step Integration

Integration of the technical process steps (identified in **Fout! Verwijzingsbron niet gevonden.**) will reduce the costs and time as follows:

- The Go/No-Go I in step 9 will indicate whether the design rules for the AM steps are correct. The cost and time related to post-processing steps for each Go/No-Go event must be added to the product's overall time/cost for production.
- The Go/No-Go in step 10 will identify whether a part has adequate stock for machining/finishing, saving costs and time at post-processing. Furthermore, the step would enable the part to be correctly set-up for machining steps.

- The polishing step 17, if automated, will attribute to a higher yield.

Output Document O.5 will conclude the cost and time reductions, taking into account the results of the technical feasibility.

1.5 Planning

1.5.1 Output Document O.3

Activities of Output Document O.3 are focussed on the validation of processes used and tool developed (compiler). The validation process will include the use of the compiler to generate, based on the scan and CAM data, a new G-code file. This file will be fed to a CNC machine and checked whether the CNC machine will start at the right point on the Mirror Object (Dry Run). No milling or polishing is involved.

1.5.2 Further Research

Activities of Output Document O.4 are focussed on the proof of principle of an integrated system, which will be set up at Hittech/MPP. These activities will include all steps from O.3, plus the milling of the Mirror Object, the quality check on the milled product and further polishing of its surface within tolerance (Physical Run).

Activities of Output O.5 are focused on the project evaluation on the Costs and Time Savings, and Technical Feasibility. The latter will be demonstrated through 'User Cases'. Both aspects of evaluation will be addressed in O.3 and O.4 too.

2 Research approach

At the core of the Demonstrator is the comparison of the data files, which are created in the various processing steps as described in the workflow (section 1.3.2).

In the set-up of the Prototype Demonstrator in the Dry Run, the various data files were compared to test whether the 3D printed objects can indeed be post processed, given its geometry (scanned), added stock, customer design and compatibility with the CNC machine and surface requirements.

As far as the validation plan O.3 is concerned, the results reported are divided into two sections:

- Technical Validation (section 3.1), and
- Costs and Time Evaluation (section 3.2).

2.1 Technical Validation Plan

O.3 is the 'Dry Run', which is a validation step in the development of the Prototype Demonstrator. The demonstrator will incorporate the lessons learned from this project's Process Development, Data Management and System Integration. The Dry Run includes the validation of the process steps 7 to 15/16, which consists of 3 components:

- Geometry control,
- Best-fit optimisation, and
- Generating the post post-processing CNC file (new G-code file).

2.1.1 Geometry Control

From the scan file, the CAD Build and CAD Stock will be subtracted. The shape left will be the general geometry of the object, which when compared with the CAD Customer, can help determine whether the shape of the 3D printed part lies within tolerances

2.1.2 Best-fit Optimisation

From the scan file, the support and stock will be removed and compared (best fit) with the CAD Customer. The best-fit will determine the orientation of the CAD Customer, which will then be compared with the CAD Stock. This test will determine whether there is enough stock on the respective surfaces for post processing

2.1.3 Generating the post post-processing (PPP) CNC file (new G-code file)

In the case where the geometry of the object is within tolerance and there is enough stock available for CNC post processing, the position of the object in reference to the EROWA table will be converted to a Translation Matrix. This Matrix will result in the post post-processing (PPP) CNC file that will be used to mill the object to net shape. The test will involve checking whether this PPP CNC file can manoeuvre the main axis of the CNC machine to the right position for milling – Go/No-go III.

2.2 Dry run test

The validation of developed process alongside the prototype tool (compiler) involved a dry-run test. The 'dry-run' is a key validation step in the development of the Prototype Demonstrator and will only focus on the process and data exchange. The validation involves the use of the compiler to generate, based on the scan and CAM data, a new G-code file for the CNC-machine. The objective of this 'dry-run' is to establish whether, based on the G-code generated, the CNC machine can then start at the correct point on the Mirror Object (shown in Figure 2). This activity is mainly a proof of concept for the process and compiler tool, and hence no milling or polishing was involved.

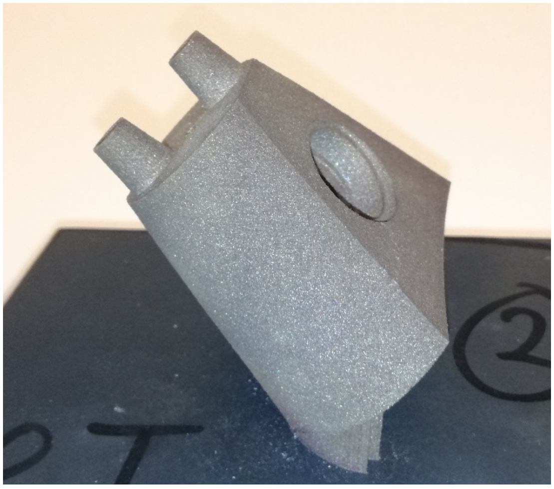

Figure 2: Mirror Object still attached to platform

The validation of process and compiler tool will be carried out using the Mirror Object as the demonstrator, and will entail the validation of the process steps 7 -> 15/16 (**Fout! Verwijzingsbron niet gevonden.**):

- The translation matrix provided by project partner Argon and the CAM based post-processing file will be used to generate a G-code suitable for CNC, then
- The accuracy of the generated file will be established through the

Commenly commercialy available operating systems for milling machines are Heidenhain, Fanuc and Siemens. , If the main axis of the CNC-machine moves to the correct position for milling, this 'dry-run' will validate the compatibility with the three operating systems.

3 RESULTS

3.1 TECHNICAL VALIDATION

3.1.1 THEORETICAL WORK

The difficulty experienced in positioning near-net-shaped 3D printed parts in a CNC machine was addressed by developing a tool to compensate for part misalignment and geometry verification. The scanning module was designed to compare the 3D scan of a clamped part to the theoretical position. A comparison between those two models results in a transformation matrix that can be used to correct the trajectories of a CNC machine (see Figure 3). The scan can also indicate if it's feasible to manufacture a correct product out of the printed part.

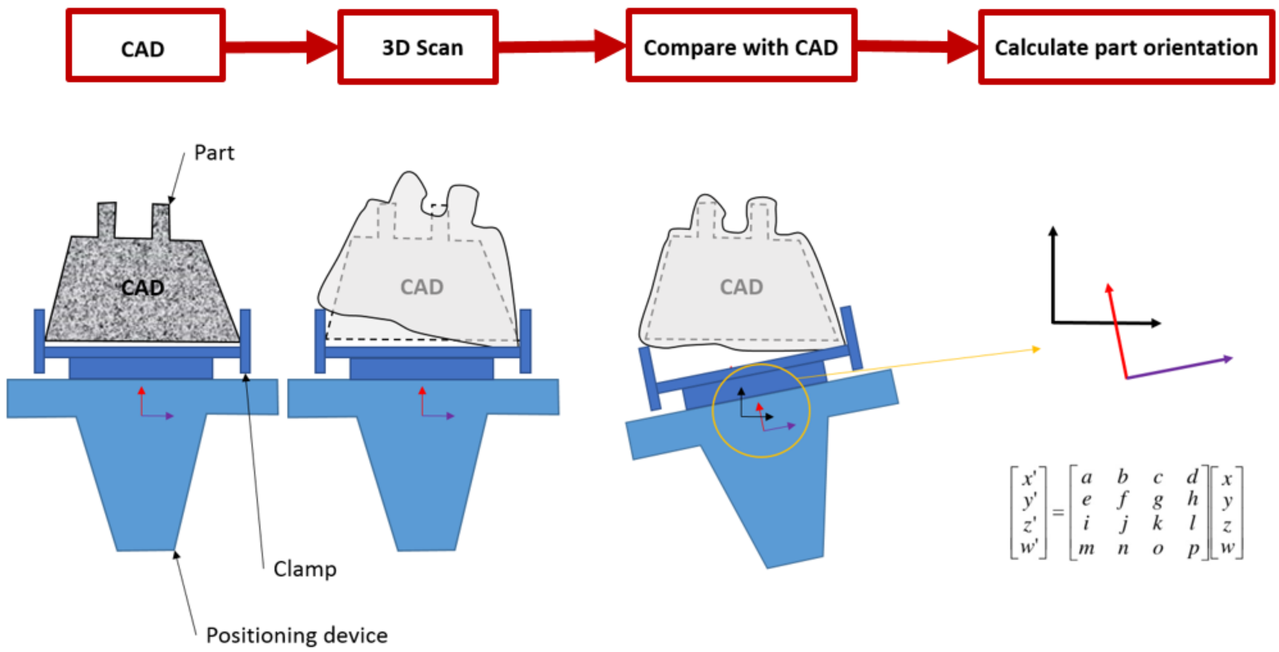

Figure 3: Visualisation of the Theoretical Work Planned and Validation carried out (image obtained from "D2.3.1 Integrated Scanning Module")

The Mirror Object was physically tested in the relevant environment, and the lessons learned from each trial was implemented into the next test. The key contributors to this development and validation were as follows:

- Argon Measuring Solutions (Argon): developed the scanning module (details of work carried out can be found in Annex 5.1);
- University of Exeter (UoE): developed the compiler that would transform G-codes based on the scanning module output values (details of work carried out can be found in Annex 5.2); and
- Hittech Multin BV (HM): provided the inputs for the scanning module and capacity to carry out the practical tests (details are noted in Section 3.1.2).
- TNO provided the knowledge and proposal for the proper clamping method (details of work carried out can be found in Annex 5.3) ….

3.1.2 EXPERIMENTAL WORK

As described in the Workflow Demonstrator:

- HM first created a 'CAD Customer' file (to represent the customer file), which defined the net shape of the end product.
- In order to be able to post process the printed part within tolerances of the 'CAD Customer' file, stock was added to the 'CAD Customer', which resulted in the 'CAD Stock' model (near net shape).

- Based on the ‘CAD Stock’ model, 3T created the ‘CAD Build’ file which combined the ‘CAD Stock’ model with the appropriate ‘Clamp’ model and the necessary ‘Support Structures’.
- Based on this ‘CAD Build’ file, HM created a CAM file for post processing the 3D printed object with CNC to its final shape.
- This CAM file is thereafter translated into a CNC machine specific post processing file (G-code file).
- This G-code file, together with scan data from Argon was fed to the CNC compiler of UoE which generated a new G-code file.
- This new G-code file was fed to a CNC machine at Hittech/Bihca to check whether the machine will start at the right point on the surface of the Mirror Object.

3.1.2.1 Dry Run 1: 10th July 2018

The first dry-run was set-up at Hittech Multin’s sister company Bihca, which is located in Winterswijk, Netherlands. The Mirror object was mounted on an EROWA table and scanned, which used the CAM-program of the Mirror object to generate its CAM zero point located on the EROWA table (see figure 4). The CAM zero point on the EROWA table is then used to generate a translation matrix based on the scan data. Thus, a G-code file is able to be generated without needing additional measurements of the Mirror object position in the CNC machine.

This set-up was verified using a five-planar artefact (FPA, see Figure 5) and the Mirror object. Both objects were scanned with a GOM-scanner, then orientated with respect to the CAM zero point (Testblok Heidenhain_DMU60), followed by checking if the CNC machine (DMU-P60, Heidenhain) orientated correctly for machining them.

Figure 4 Setup dry-run test

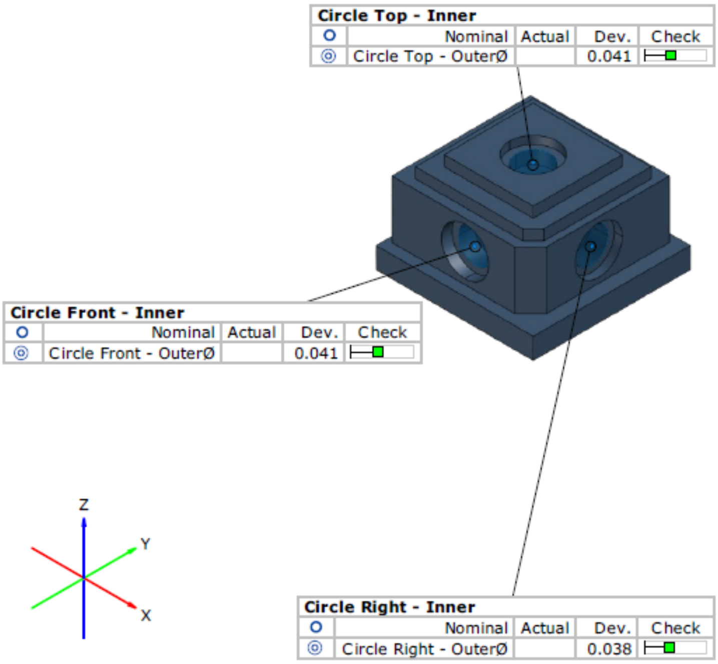

Figure 5: Details of the Five Planar Artefact, FPA (image obtained from "D2.3.1 Integrated Scanning Module")

It was observed that the CNC machine did not orientate as expected, and further investigation proved that 'constructing' a 'start' coordinate system using a virtual point (CAM zero point generated) was difficult. Thus, this process could not be validated at this point. It was determined that the starting point of CAM must be related to the Erowa table, and that the CAD starting point must be related to physical geometry.

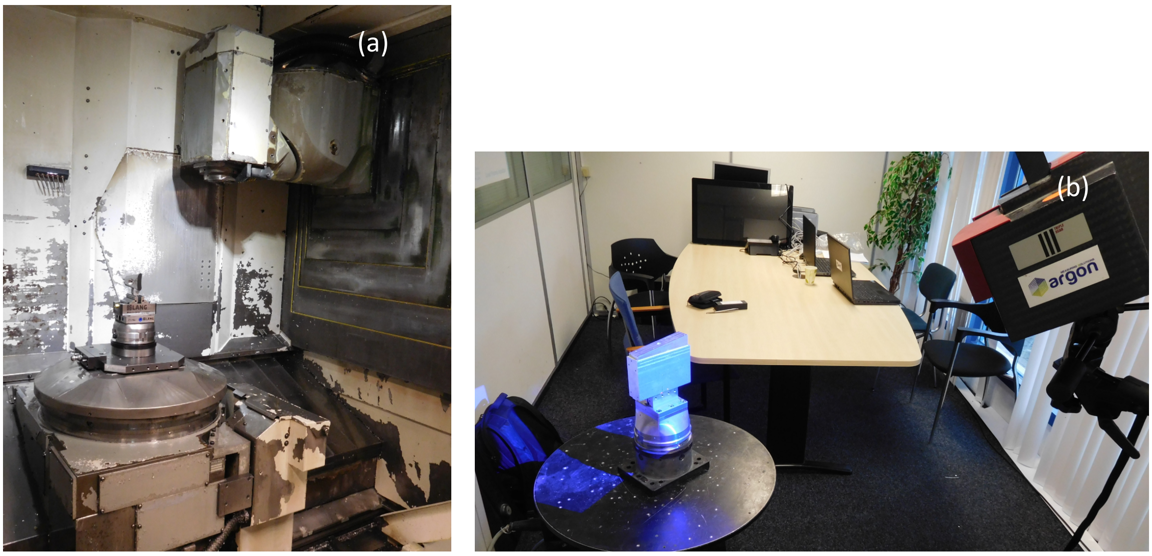

Figure 6: Image of (a) CNC set-up and (b) scan in progress

3.1.2.2 Dry Run 2: 30th August 2018

The second dry-run was also set-up at Bihca, using the same CNC machine (DMU-P60, Heidenhain). Once again the Mirror object (mounted on an EROWA table) was GOM scanned, and the CAM-program of the Mirror object (Testblok Heidenhain_DMU60-palletnulpunt.H) was used to generate a transformation matrix as input for compiler. The compiler (Figure 7) then compiled NC files to new coordinates (DMU 60-

Palletnulpunt_cadnulpunt_45gr.H). Finally, the orientation of the CNC machine was checked for accuracy and to verify this process.

It was again observed that the CNC machine did not orientate as expected, and the predicted rotation angle did not correspond. It was also noted that a small angle in a certain (second) axis resulted in a complex movement of the machine bed, and the Z-value was not correct when the Erowa zero-point was not known by the operator. Hence this process could not be validated either.

Further investigation into the cause indicated that the CNC machine made use of a left-handed coordinate system, and that the "CPL" coordinates are not defining the CPL itself but the position where the machine is orientated to. Thus, it was decided that only 1 axis of rotation should be used during testing.

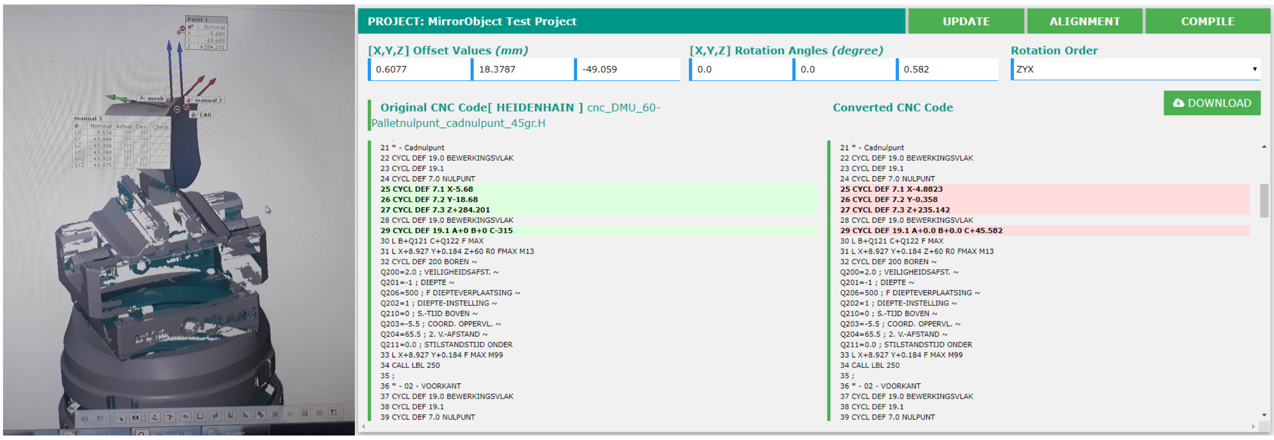

Figure 7: Screenshot of compiler in action

3.1.2.3 Dry Run 3: 11th September 2018

The final dry-run was set-up at Hittech Multin MPP, the CNC machine used was DMU-60P – Millplus, and the CAM file was DMU 60-Pallet-40-graden-Original. One of the objectives of this test was to understand the role of CPL in CAM with regards to EROWA zero-point, make use of the rotated part in CAM, as well as validate the process through accurate machine axis movement/orientation.

The test indicated that when the machine is moved to CPL position, the movements are relative to tool, and the machine calculates its position to orientate to CPL. It was concluded that the first CPL defines the real part position, and from there, the transformation matrix can be used (Figure 9). This test was thus successful in validating this process.

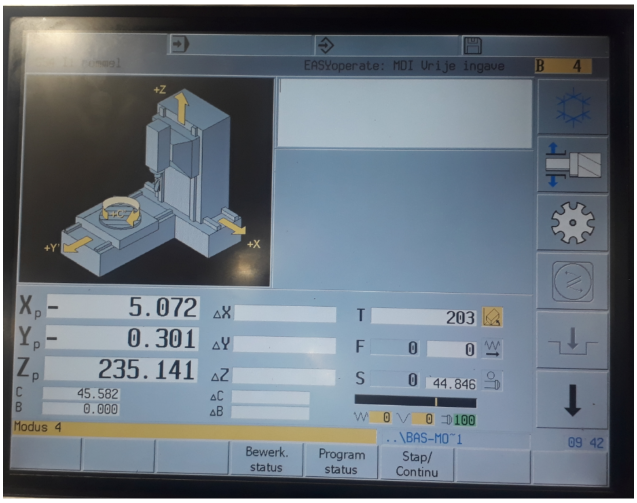

Figure 8: Screenshot of machine axis calculations

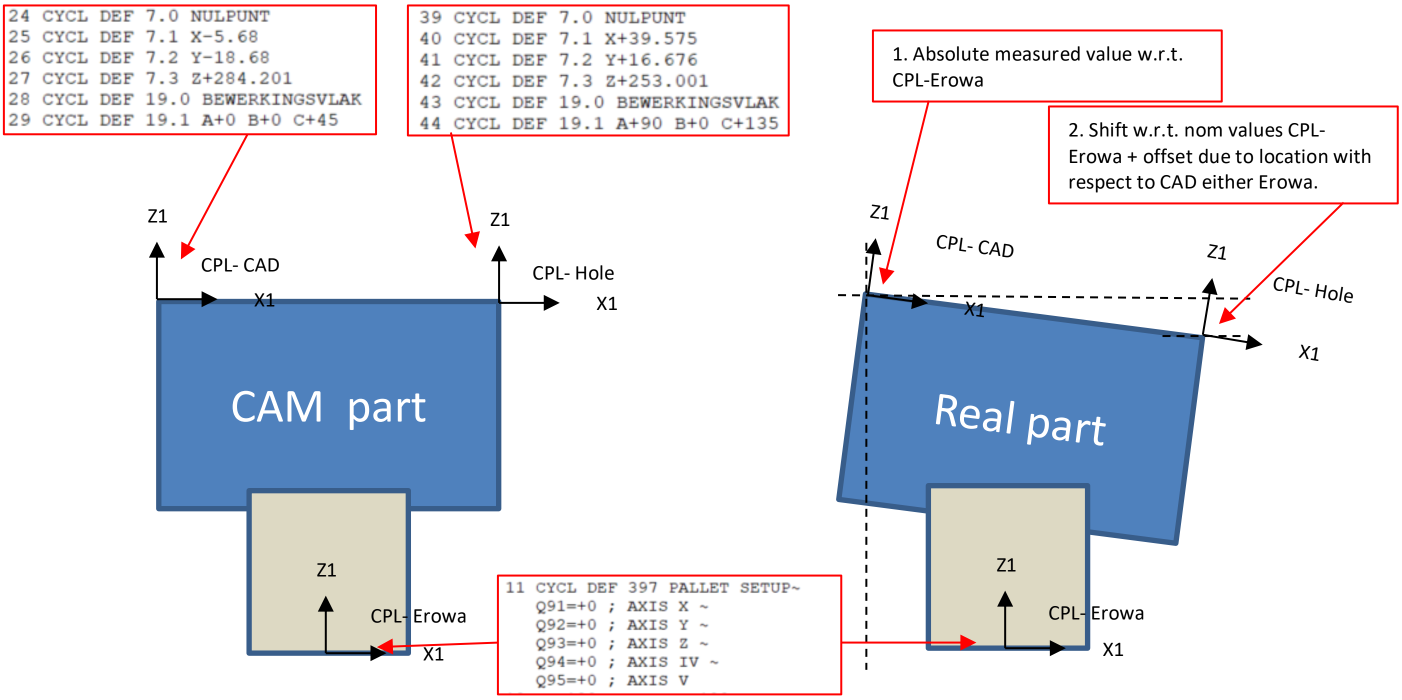

Figure 9: Transformation Matrix

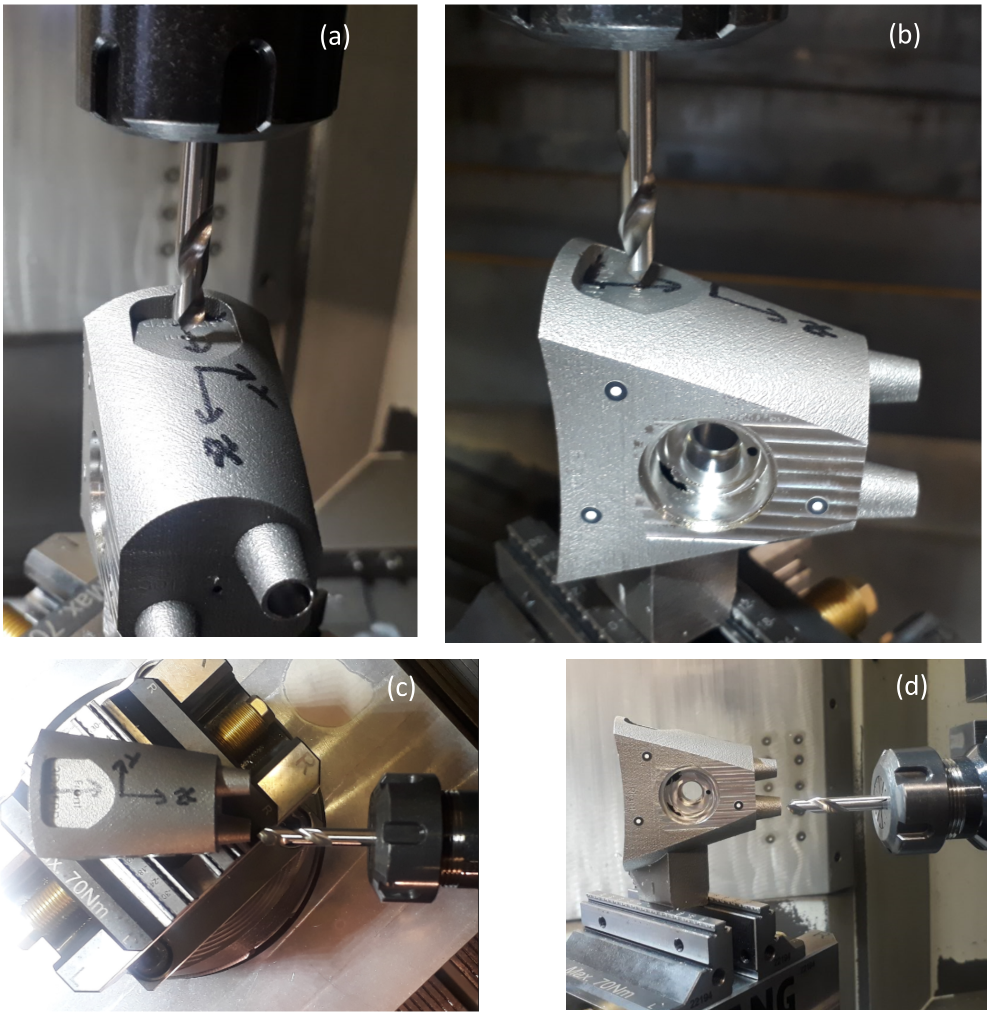

Figure 10: MPP-60P at (a-b) CPL1 and (c-d) CPL2

3.2 Cost and Time Evaluation

The 3D&FPP project goal is to achieve a 30% cost reduction and a 50% time saving with respect to current methods of post processing. The following paragraphs will elaborate on how the proposed system approach of the Demonstrator will result in realizing these objectives.

3.2.1 Cost Reduction: Demonstrating Reduction Yield Loss

The 3D&FPP approach of post processing is mainly aimed at the prevention of yield loss, which in effect is a cost reduction. The current overall yield loss of 3D printed parts and generally accepted by the 3D printing industries, is set at 10% (source: project partner 3T).

Of this 10%, 70% is directly detected as a loss (visually, measurements, etc.). However, 30% of the overall yield loss is detected only upon final inspection of the final product, which is of course after post-processing is complete.

This 30% yield loss after post processing can be attributed to two key factors:

- poor post-processing, such as CNC, hand-finish, etc. (50% estimated), and/or
- the printed part did not meet the criteria for post processing and should not have been processed in the first place (50% estimated).

The proposed process steps in which the CAD/CAM/Scanning files are compared to create a new NC-post, ensures that the printed part can indeed be post-processed and ensures the post-process will indeed result in a 100% yield.

Hence, the proposed post-processing steps could therefore decrease the yield loss upon final inspection by **50%,** when set against the current loss on printed items which are NOT detected before processing.

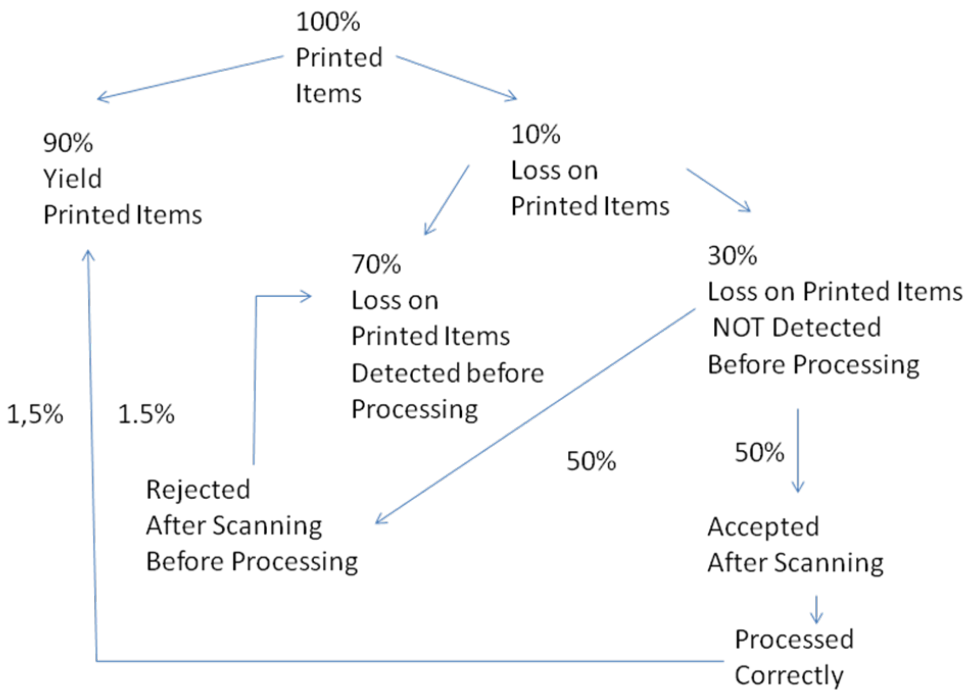

Figure 11: Analysis of current yield and costs

However, a fully integrated post-processing process can yield more cost effectiveness (less labour, less material, effect of large batches, etc.). These potential costs effectiveness will be elaborated on in Output Document O.4 and O.5.

3.2.2 Time Reduction

How a fully integrated post-processing process will impact the overall production time will also be studied in conjunction with the costs effectiveness and elaborated on in Output Document O.4 and O.5.

4 Conclusion

To summarise, the scanning module, programmed with an ATOS triple scan in the GOM software, generated a transformation matrix which was used as input to modify the CNC code. It considered the general surface tolerances and local stock requirements. The functionality, accuracy and repeatability of the scanning module was tested during multiple test runs at Hittech (example of the set-up on Figure 12). The scan measurements of test objects were successfully used to calculate the relevant transformation matrix and modify the CNC code. The approach as defined for the scanning module has therefore been validated and can be further tested on different user cases in WP3.

Figure 12: Set-up for dry-run 3 at Hittech Multin

4.1 Increase in TRL

According to EU's Horizon 2020 description:

- TRL5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies), and
- TRL6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).

The flexible postprocessing solution was successfully demonstrated in a relevant industrial environment. Based on the description its TRL level progressed from 5 to 6.

5 ANNEXES

5.1 SCANNING SOLUTION

Activity 2.3 Definition of the scanning solution as to mapping 3D printed parts resulting in a description of the scanning solution to be integrated in the post processing production chain. The scanning solution describes the possibilities to generate a qualitative 3D measurement (STL-file). It was programmed in the GOM software and generates transformation matrix used as input to modify the CNC code. It considers the surface tolerances and local stock requirements. The scanning module was tested during multiple test runs at Hittech. The scan measurements were successfully used to calculate the transformation matrix and modify the CNC code.

5.2 DESIGN RULES

Activity 2.6 Define design rules derived from the requirements for clamping, scanning, machining and polishing resulted in the description of the integrated solution for post machining of 3D printed metal parts. The proposed solution aims to facilitate the post machining of 3D printed parts through automatic modification of preprogramed CNC code based on the real position of clamped part obtained via comparing of the 3D scanned model with the original CAD model. To guarantee satisfactory performance of the proposed solution, a series of rules or guidelines are proposed to guide the operations along the integrated work flow. These guidelines comprise:

- the additional stock on milled and round surfaces
- minimization of support structure
- permittable cutting allowance
- reference features for model alignment
- processes for stress relieve, cleaning and preparing scanning

5.3 CLAMPING PRINCIPLE

Activity 2.2 Analysis and evaluation of the clamping principle and clamping equipment and effect on part accuracy yielded the description of the flexible clamping solution to be integrated in the post processing production chain. The solution consists of 2 process steps:

- adding a clamping handle and
- clamping with universal pin clamp.

In this research the design and orientation of the printed handle is discussed and described. The deliverable also comprises a CAD file for designing the clamping handle

5.4 LIST OF USED ABBREVIATIONS

Abbreviation	**Explanation**
AM	Additive manufacturing
ATOS	Trademark for digital
CAD	Computer aided design
CAM	Computer aided manufacturing
CNC	Computer numerical control
CPL	Center point load
EROWA	Trademark for clamping systems
FPA	Five-planar artefact
GOM	Trademark of software for industrial metrology
NC	Numerical control
OEM	Original equipment manufacturer
TRL	Technology readiness level