3D&FPP

Interreg 2 Seas Mers Zeeën

European Regional Development Fund

Integrating Metal 3D Printing & Flexible Post Processing

System integration and validation
(including O4 &O5 output reports)

Application form: ***2S01097 3D&FPP***

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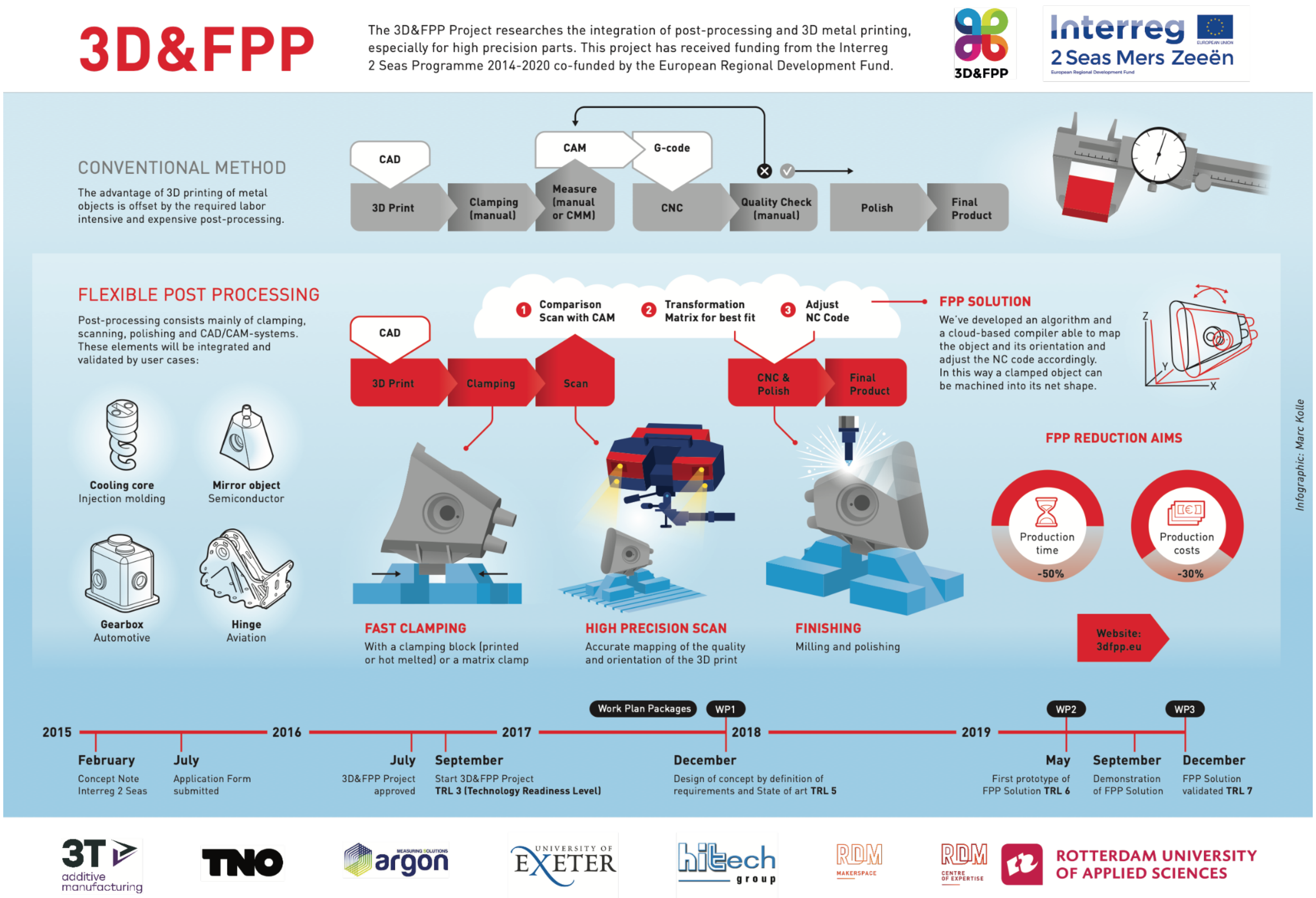

3D&FPP
The 3D&FPP Project researches the integration of post-processing and 3D metal printing, especially for high precision parts. This project has received funding from the Interreg 2 Seas Programme 2014-2020 co-funded by the European Regional Development Fund.
3D&FPP
Interreg
2 Seas Mers Zeeën
CONVENTIONAL METHOD
The advantage of 3D printing of metal objects is offset by the required labor intensive and expensive post-processing.
CAD
3D Print
Clamping (manual)
CAM
Measure (manual or CMM)
G-code
CNC
Quality Check (manual)
Polish
Final Product
FLEXIBLE POST PROCESSING
Post-processing consists mainly of clamping, scanning, polishing and CAD/CAM-systems. These elements will be integrated and validated by user cases:
Cooling core
Injection molding
Mirror object
Semiconductor
Gearbox
Automotive
Hinge
Aviation
1 Comparison Scan with CAM
2 Transformation Matrix for best fit
3 Adjust NC Code
CAD
3D Print
Clamping
Scan
CNC & Polish
Final Product
FPP SOLUTION
We've developed an algorithm and a cloud-based compiler able to map the object and its orientation and adjust the NC code accordingly. In this way a clamped object can be machined into its net shape.
FAST CLAMPING
With a clamping block (printed or hot melted) or a matrix clamp
HIGH PRECISION SCAN
Accurate mapping of the quality and orientation of the 3D print
FINISHING
Milling and polishing
FPP REDUCTION AIMS
Production time -50%
Production costs -30%
Website: 3dfpp.eu
Infographic: Marc Kolle
Work Plan Packages
WP1
WP2
WP3
2015
2016
2017
2018
2019
February
Concept Note Interreg 2 Seas
July
Application Form submitted
July
3D&FPP Project approved
September
Start 3D&FPP Project TRL 3 (Technology Readiness Level)
December
Design of concept by definition of requirements and State of art TRL 5
May
First prototype of FPP Solution TRL 6
September
Demonstration of FPP Solution
December
FPP Solution validated TRL 7
3T additive manufacturing
TNO
argon
UNIVERSITY OF EXETER
hittech group
RDM MAKERSPACE
RDM CENTRE OF EXPERTISE
ROTTERDAM UNIVERSITY OF APPLIED SCIENCES

Summary

Integration of post processing requires smart solutions for clamping, mapping , milling and polishing, which have to be implemented into one, smart and efficient production chain. The challenge is to locate and map the object, establish and translate the required post processing steps with a minimum of support structures and reclamping and repositioning actions. This proved to be a mere quest of interfacing and IT. On top of that, the 3D&FPP projects' goal is to design a process that works as an add-on to existing machines.

The FPP was demonstrated with the aid of user cases stemming from different disciplines like the maritime, automotive, cleantech and aviation industry. Drawing from experience and in close contact with relevant parties, Hittech Multin has designed the Mirror Object, a special designed object comprising all complexities in 3D printing, clamping, milling and polishing. During the project the Mirror Object has served as the main subject for research, all other user cases have been referenced to this object.

As solution for integrating 3D metal printing and flexible post processing, the partnership has developed an algorithm with a cloud-based compiler. This Flexible Post Processing solution (FPP) is able to align all available data from various sources, and automatically creates an adjusted machine code, the NC-code, to post process the object on a milling machine according to spec.

The FPP solution encompasses existing technology that can be integrated, making post processing an inexpensive and time efficient activity. The validation tests of the FPP approach show the suggested solution does fulfil the requirements for industrial high precision application and the solution is generic for it supports the three main operating systems (Heidenhain, Fanuk and Siemens) currently dominating the industry. Since existing machines have a typical lifespan of 10-15 years, the project has a significant impact in the short term.

The FPP solution has been successfully validated and demonstrated using user cases during a full scale dry run test and live demonstration on a compact setup of the FPP.
The FPP approach is a viable and validated way of work at technology Readiness Level (TRL) 7. Its contribution to a more cost and time efficient process highly depends on the type of product, the products requirements and manufacturer specific production settings. The developed calculation model developed by the 3D&FPP partnership will serve as a tool for manufacturers to assess the applicability of the FPP approach taking into account all their production specifics which impact the costs and time savings implied.

The achieved reduction also highly depends on applied batch size. From the cost calculation model, it is determined, given de project's production settings, that for the Mirror Object the cost reduction for a single product is 14% on the total costs and 26% on postprocessing.
As the research aimed at a cost reduction of 30%, the achieved reduction of 26% for post processing is an important and significant improvement.

The project aimed for 50% reduction in production time. The achieved lead time improvement is 7,5%, which is significantly lower. However, in the field of 3D printing 7,5% is considered an important lead time improvement.

Version Control

Version	Date	Description
1.0	November 25th 2019	First draft
2.0	December 27th 2019	Edited by TNO
3.0	January 2nd 2020	Future developments and recommendations added
4.0	January 8th 2020	User case comparison added, final version
4.1	January 17th 2020	Editorial and layout changes
4.2	January 24th 2020	Editorial and layout changes

CONTENTS

1 Introduction

In 2016 the 3D&FPP partnership was granted funding from the Interreg 2Seas Programme[1] for their project on Integrating Metal 3D Printing & Flexible Post Processing, or 3D&FPP.

1.1 Objective Interreg 2 Seas

The overall objective of the Interreg 2 Seas programme is to develop an innovative, knowledge and research based, sustainable and inclusive 2 Seas area, where natural resources are protected, and the green economy is promoted. The Interreg 2 Seas strategy is based upon four Programme Priority Axes, which in turn are broken down into seven Specific Objectives. Both elements are Programme-specific but are consistent with the chosen thematic objectives and investment priorities as defined in the EU Regulations. The 3D&FPP project is classified as Specific Objective 1.2: Technological Innovation, which focusses on smart specialisation sectors, including manufacturing.

1.2 Challenge in Additive Manufacturing

Additive Manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Nowadays, there are techniques to mill, to polish, to clamp and to map a printed part but these techniques are not integrated in a process, making post processing an expensive, inefficient and time-consuming activity. A major challenge for the industry is to move this emergent technology forward from its prototyping history into a true manufacturing capability.

Whenever a part is 3D printed, the object does not comply with specified requirements and requires some processing: removal from the build plate, removal of support material and cleaning. On top of that, the surface roughness is too high for conventional positioning and certain details (position of one surface in relation to another, holes, dimensions) are not within specified tolerances. This is illustrated in Figure 1, a hinge from the aviation industry.

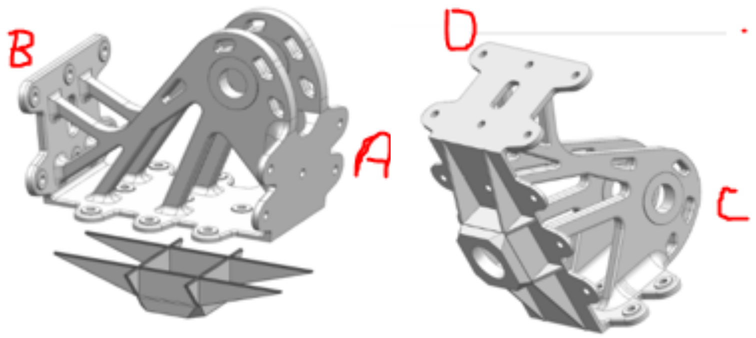


Figure 1 The Hinge user case

The 3D printed hinge shows the areas that need post processing: the two surfaces (A and B) that will be mounted on the plane need to be perfectly smooth, the holes (C) for the screws (D) need to be at the exact right place and the orientation of the surfaces in relation to each other need to be within a 0.1mm and 0.1 degree accuracy

[1] The Interreg 2 Seas programme 2014-2020 is co-funded by the European Regional Development Fund

Post processing is therefore a time-consuming process which consists of a lot of human activities and expensive machinery is used. In the 3DFPP approach the human intervention is eliminated as much as possible, reducing the chance of human induced errors. While transferring procedures outside of the expensive five axes milling machine. Which increases the available machine time of the milling machines. This approach saves production time as well as production costs.

1.3 Objective 3D&FPP

Interreg 2 Seas project 3D&FPP aims to result in a reduction of production time of 50% and a reduction of production cost of 30% of post processing. The project's objective is to design, develop and implement one efficient, fast and affordable post processing solution based on existing technology that can be part of an integrated system for post processing AM parts. This will help to significantly increase the possibilities for 3D metal printing in industries that need high precision manufactured metal parts e.g. medical industry, semiconductor industry, maritime industry, aviation, and new emergent clean tech industries. The project will bring the post processing tool and process that can be integrated with the 3D metal printing process from TRL level 3 to 7.

1.4 Cross-border approach

Knowledge and skills are dispersed among the regions; with this project, they can be aligned. For this project, we need expertise and skills on both 3D printing and on high precision post processing and on the needs of maritime, aviation, and semiconductor industry in the 2 Seas regions. Our partners have this knowledge and the power to implement the needed activities to reach the output of the project. It will provide the partners with the chance to combine knowledge, facilities and research capacity into strong partnerships and can tap into the innovative potential of the regions.

The project partners represent public and private organizations, as well as universities, research institutes and SME's across the 2Seas region:

- Rotterdam University of Applied Sciences (lead partner, NL)
- RDM Makerspace (NL)
- TNO (NL)
- Hittech Multin (NL)
- 3T RPD (UK)
- University of Exeter (UK)
- ARGON Measuring Solutions (BE)

Each partner represents a specific expertise, vital for the research in this project:

- 3D printing and production: 3T AM
- 3D printing and clamping: TNO
- CAD/CAM Interface design and algorithm development: University of Exeter
- 3D Scanning and mapping objects: Argon Measuring Solutions
- Precision engineering, milling and polishing: Hittech Multin
- Dissemination and demonstration: RDM Makerspace
- Innovation, education and piloting: Rotterdam University of applied Sciences

1.5 Observer partners

Besides the project partners, 24 observer partners supporting the 3F&FPP project play a crucial role in the dissemination, exploiting and valorisation of the project outputs.
The observer partner organizations from (mainly) the Interreg 2 Seas regions of 3D&FPP are:

- 3D Makers Zone (NL)
- Additive Industries (NL)
- Dredging International (BE)
- European Society for Precision Engineering and Nanotechnology (UK)
- Flanders Additive Manufacturing and 3D Printing Ecosystem (BE)
- Flanders Make (BE)
- Fokker Technologies Holding (NL)
- Heerema Fabrication Group (NL)
- Holland Instrumentation (NL)
- Huisman Equipment (NL)
- InnovationQuarter (NL)
- Leidse instrumentmakers School (NL)
- Machine factory Bolier (NL)
- MAPPER Lithography (NL)
- Maritime Research Institute Netherlands (NL)
- Martek Marine (UK)
- Matikem (FR)
- Metal Technics 3D (BE)
- Netherlands Aerospace Centre (NL)
- Netherlands Maritime Technology Foundation (NL)
- Northern France Innovation Development (FR)
- Prima Industries (IT)
- Rotterdam FieldLab Additive Manufacturing (NL)
- VOLUM-e 3D complex production (FR)

1.6 Reading guide

Doing an Interreg 2Seas project implies reporting according to the Application Form (AF). The 3D&FPP research is arranged in five workpackages. Each workpackage results in deliverables and outputs and are reported in Output documents. The present report represents the final output reports of Workpackage 3:

- O4.1 Prototype and
- O5.1 Demonstrated user cases.

The reading guide indicates the reference to the AF.

In chapter 2 the overall research approach and the research roadmap is described based on the AF as approved in January 2019.

The description of the Flexible Post Processing solution (FPP) is given in chapter 3. It describes the system of conventional post processing, the FPP approach and the resulting design rules for 3D printing and post processing.

According the Application Form submitted 14.12.2018, this chapter is to be regarded as Output report O4: “Prototype of integrated 3D printing and high precision postprocessing manufacturing setup”.

The description of the demonstration setup, qualitative analysis of the FPP in terms of reduction in production time and costs and consequences for the different user cases, is described in chapter 4. According the Application Form submitted 14.12.2018, this chapter is to be regarded as Output report O5: “Demonstrated user cases in pilot”.

Chapter 5 reflects on the achieved feasibility (Technology Readiness Level, or TRL) and retrofit capabilities of the FPP. It also discusses the general conclusions of the project and some recommendations for further research and development.

All mentioned output reports are available for downloading at
http://www.3dfpp.eu/downloads/Output-reports/

2 Research roadmap

The 3D&FPP project aims to design, develop and implement one efficient, fast and affordable post processing solution based on existing technology that can be part of an integrated system for post processing AM parts. This implies four main elements need to be integrated: clamping, scanning, polishing and CAD/CAM-systems. The project was therefore arranged in three dedicated research work packages (WP):

1. Design (Workpackage 1),
2. Development (Workpackage 2) and
3. Pilot user cases (Workpackage 3)

Two other work packages comprised the overall project management and monitoring (WP4) and communication of the project (WP5). Because they are not part of the research, it will not be discussed in this report.

2.1 Design (Workpackage 1),

In the Design phase of the project, the requirements were set, the state of the art was studied, and user cases were defined. The State of Art research resulted in the definition of the requirements for the separate steps of post processing. In turn, these requirements provide a design and proposal for improvements for the integration of post processing and 3D metal printing. This research is reported in output documents O1.1 Feasibility research and O2.1Feasibility test. See http://www.3dfpp.eu/downloads/Output-reports/ to download the report.

2.2 Development (Workpackage 2)

In the Development phase (WP2) of the project, the approach of integration is defined. Together with the requirement studies, the first contour, consequences and challenges for an integrated design were set. Integration of the various post processing steps (clamping, scanning, CAD/CAM and polishing) proved to be a challenge, for each step has its own interface and requirements, while the integration is to be applied not only to the printing and post processing production itself, but for the workflow and the design principles as well. In order to tackle the defined challenges, a Fast Prototyping Approach (FPA) was applied, which means early testing and verification of the concept in separate steps. This research is reported in output report O3.1 Development of prototype. See http://www.3dfpp.eu/downloads/Output-reports/ to download the report.

2.3 Pilot user cases (Workpackage 3)

The main objective of this WP is the actual physical integration and demonstration of the integrated 3D printing and post processing production prototype. The prototype was demonstrated with the aid of user cases, some of which were provided by observer partners and also used for validation of the final solution. This research is reported in the present report: O4.1 Prototype and O5.1 Demonstrated user cases. See http://www.3dfpp.eu/downloads/Output-reports/ to download the report.

3 Description of FPP Prototype (O4)

3.1 Introduction

The moment a 3D printed part is taken out of the 3D printer, all reference of the part to its exact location and orientation is lost. With each process step having its unique set of requirements, origins and offsets, defining a flexible and universal solution is a mere quest for 'zero's and origins'. Therefore, integration of 3D metal printing and post processing proved to be a software interfacing challenge. On top of that, most 3D printed parts don't have a flat surface to mount the object onto a clamp and conventional clamping could deform the shape and endanger the integrity of the object.

If we want to post process the part, we need to establish the actual shape and orientation of the part and solve the problem of clamping. The requirements and state of art studies resulted in the definition of a possible approach for flexible post processing (FPP).

3.2 Description of FPP

The main difference between conventional post processing and integrated post processing flexible is in the way the shape and orientation of the part is determined, see Figure 2.

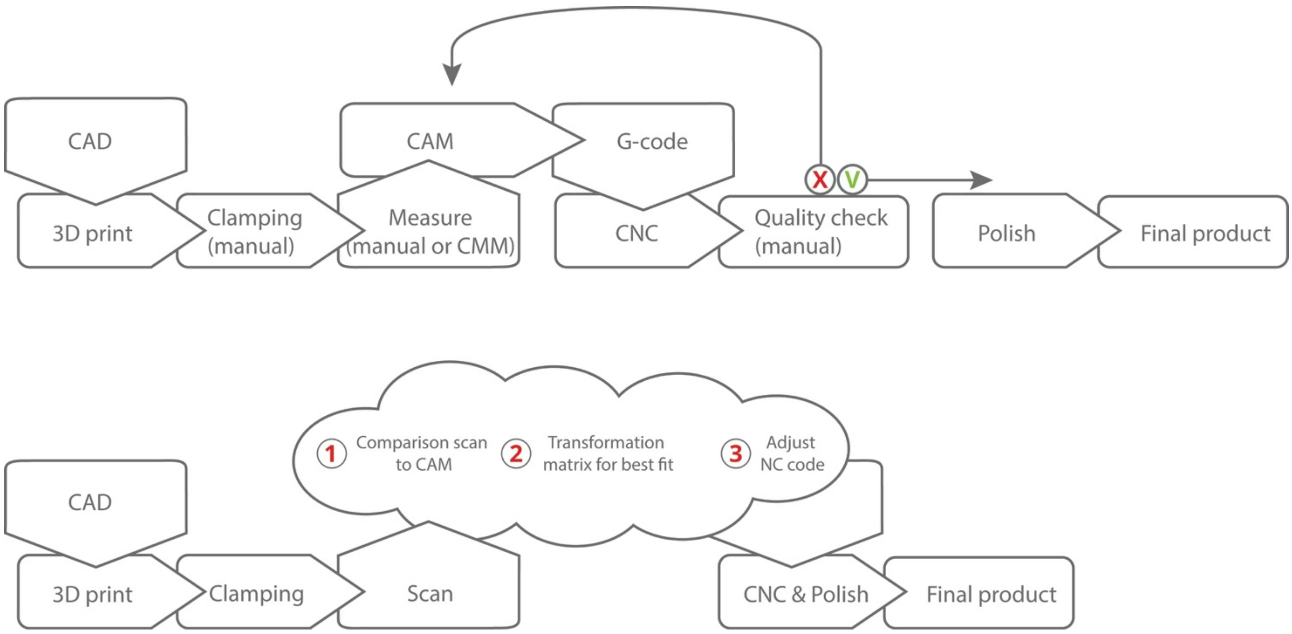


Figure 2 Conventional (above) and integrated (below) post processing

Data integration from various software packages for CAD, CAM, scanners and CNC-mills is considered to be key in speeding up the post-processing procedures. All information concerning position and orientation of the object for post processing purposes is lost as soon as the object leaves the 3D printer. This Flexible Post Processing solution (FPP) compares the scanned data from a clamped printed object to its CAD information. It is able to determine the scanned orientation with respect to the clamp, as well as the optimal fit to mill the net shape object with the required tolerance. The FPP then aligns all available data from various sources, and automatically creates an adjusted machine code, the NC-code, to post process the object on a milling machine according to spec.

3.3 Design Rules

The proposed solution aims to facilitate the post machining of 3D printed parts through automatic modification of pre-programmed CNC code. This is based on the real position of clamped parts obtained via comparing the 3D scanned model to the original CAD model. To guarantee satisfactory performance of the proposed solution, a series of rules or guidelines are required to guide the operations along the integrated workflow, see Figure 3.

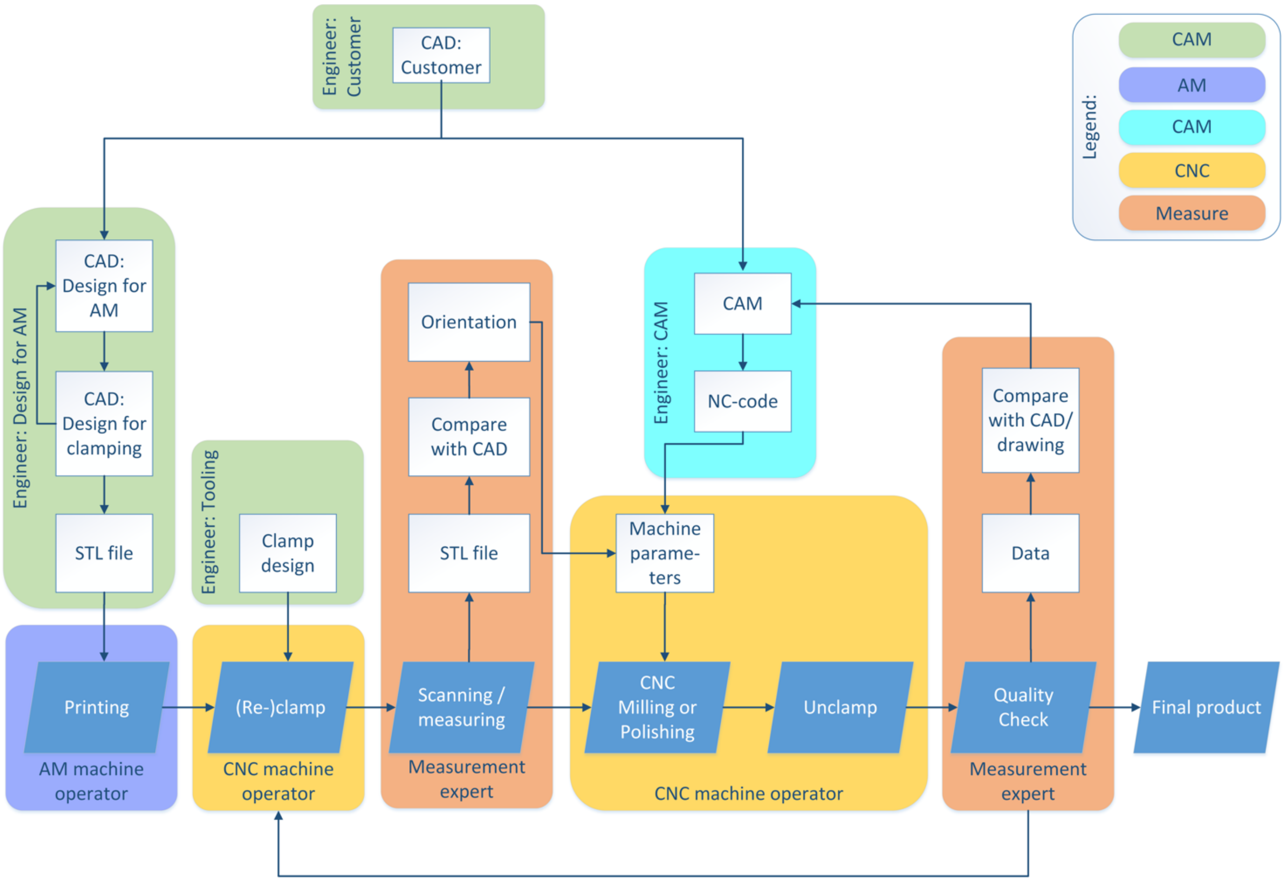


Figure 3 Integrated workflow of post-machining of 3D metal printed parts

The integrated workflow starts with the original CAD model along with the post-machining CAM programming, which includes the original NC-code.

Given the original CAD model, a printable 3D model (in STL format) needs to be generated through properly orientating the original CAD model, adding cutting allowance and/or clamp/reference structures, and generating appropriate support structures for the AM process. The printable 3D model can then be produced using metal 3D printing, followed by heat-treatment, support removal, offline clamping, and 3D scanning to get the digital 3D model of the clamped part.

To integrate with the post-processing system usually conducted by a CNC operator, the scanned 3D model will be compared with the CAD model used for CAM programming to obtain the transformation matrix from the theoretical position to its real position in post-processing system. To this end a Compiler has been developed which updates the original NC-code automatically according to the transformation matrix obtained through model alignment.

The rules/advices for each step are presented in the following sections. A more detailed description of the design rules mentioned above can be found in the Online Design Guide at www.3dfpp.eu/downloads/tools.

3.3.1 Design requirements with respect to the use of software

CAD&CAM

The integrated workflow starts with the original CAD model along with the model requirements provided by the customer.
The CAD model should be represented as a 3D mesh model (in STL format) and contains the position information same as defined in the CNC code. In other words, the origin (zero point) and the coordinate system of the STL file have to be the same as used in CAM programming.

CNC Code

For automatic compiling, the CNC code must be programmed based on tilting work plane (TWP, see figure 2) which is supported by major CNC controllers such as HEIDENHAIN, FUNAC, and SIEMENS. Moreover, the following information has to be provided along with the CNC file:

- Specifications of CNC controller including type and version;
- Programming standards: ISO or CYCLE.

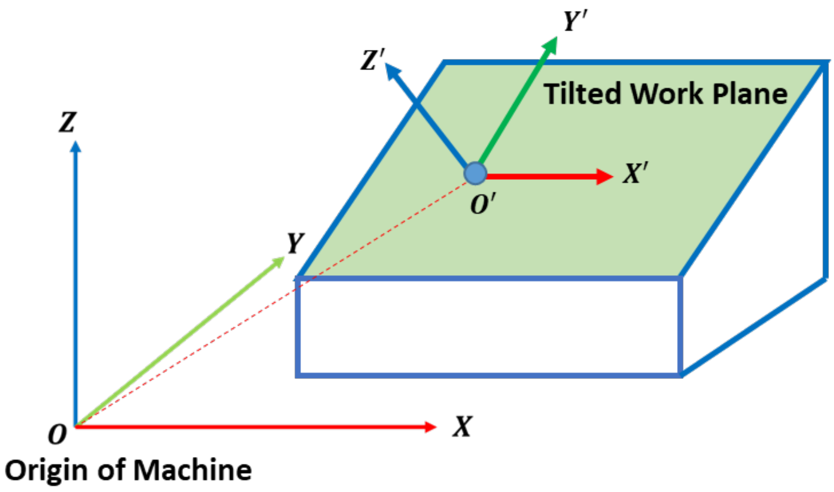


Figure 4 Illustration of tilted work plane (TWP)

3.3.2 Design Requirements with respect to Additive Manufacturing (powder bed technology)

The design considerations for 3D printing depend on the specific manufacturing technology – in this case for powder bed technology. To guarantee the printed metal parts have enough material ('stock') for further milling, the original CAD model usually needs to be adjusted for cutting operations by adding stock material.

When designing a part optimised for metal AM there are several factors to consider that will influence the design decisions.

Quantity

The quantity of part(s) and therefore the part density of the platform is one of the key components to consider when determining the build orientation.

Support structure

When designing for metal AM the ultimate goal should be to produce a geometry which is completely self-supporting (i.e. requires no additional support structure). This may not always be possible but choosing an orientation for the part which requires the least amount of additional support will help to reduce material costs and the amount of post processing the part requires.

Part Strength

A good rule to ensure a stable part is to ensure the ratio between the section and the height is no more than 8:1, as exceeding this ratio might damage the part alongside adjacent parts. These issues are can be prevented by bridging the vertical sections at frequent intervals to form a more rigid structure. Arching the horizontal bridges will ensure they are self-supporting and avoid the need for additional support structures. This is illustrated in figures 5 and 6 Figure 5 shows from left to right:

- Height to width ratio of 8:1 is optimal for part stability;
- Parts that are higher than this ratio may get damaged during recoating, may damage adjacent parts and/or build crashes;
- Frequent horizontal bridges can strengthen the part during during build;

Figure 5 Additional supports,

Figure 6 shows, from left to right:
- Some geometry may be strong on completion, but require additional support during the build process;
- Simple support structure can sometime strengthen a part throughout the build process;
- A slight re-design (introduction of perforated surface in this case) may provide adequate support, maintain the reduced weight while minimise support structure requirements.

Figure 6 Additional supports

Angled Surfaces
Unlike polymers, metal powder in the build chamber does not provide any support to layers being built above it. Depending on the material, some angled surfaces, despite having downward facing surfaces, are self-supporting. Support structures will be required however, if the angle is too acute. Furthermore, if support structures are required near the angle, the downward facing surface may require significant amount of post-processing to reduce the surface roughness.

Downward Facing Surfaces/Cut-outs
All geometries with downward facing surfaces will require support structures, which will subsequently require removal and surface finish. There are various approaches to deal with downward facing surfaces, which are described in more detail in the Online Design Guide (www.3dfpp.eu)

Downward Facing Surfaces/Overhangs
Horizontal overhanging surfaces present the same challenge as downwards facing surfaces in cut-outs, and thus, can be dealt with using similar approaches.

Holes
Small holes up to a maximum of 6mm diameter can be accommodated by the process without the requirement for support structure. Holes larger than 6mm are more likely to have a very rough, low density surface at the top which may require post processing (Figure 7).

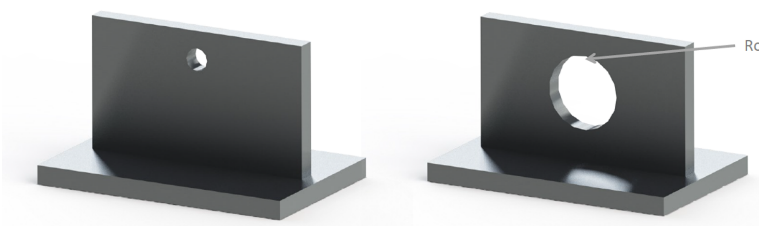


Figure 7 Holes

The addition of support structure into larger holes will help improve roundness and the surface finish of the downward facing surfaces. It will also prevent the hole from collapsing or distorting. A teardrop shaped hole is very effective as it will not require any support structure but can still offer the same material reduction benefits (Figure 8).

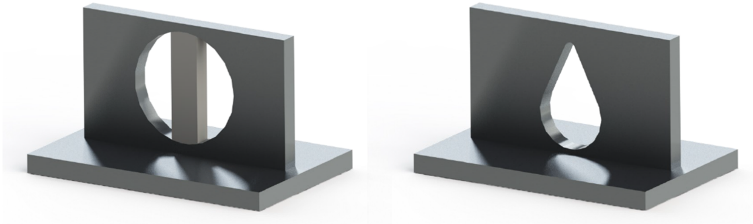


Figure 8 Supported holes

3.3.3 Design requirements with respect to Clamping

Before 3D scanning, the printed parts need to be securely clamped either onto the CNC machine or onto the offline clamping system, see an overview in Figure 9. However, offline clamping and scanning are highly recommended to reduce the occupation of CNC machines. Offline clamping and mapping will reduce the loss of machine operating time and the CNC operator time.

Three methods of clamping are applied in this research:

- Standard clamping, including zero point clamping solutions
- Flexible clamping, with the aid of an additional printed handle for claping complex objects in standard clamping tools
- Soft clamping, for post processing the 6th surface.

The samples should be clamped with a type of Zero Point Clamping system (ZPC) in preparation for 3D scanning. A ZPC system (see Figure 10), for example by LANG® usually consists of Quick Point Plates (base station), Adaptor Plates, Risers, Tombstones, and Grips (work holders). The relative position of Grips (work holder) to the Quick Point Plate (base station) is calculable based on the specifications of the components, and the Quick Point Plate (base station) usually located at the Origin of the machine. Therefore, the relative position of the sample to the origin of the machine can be calculated provided that its relative position to the Grip (work holder) was known.

Figure 9 Example of clamping portfolio Schunk

Figure 10 Example zero point clamping systems (Erowa)

Regarding the 3D printed products with complex geometry, a flexible clamping structure is recommended. Therefor 2 clamping setups are proposed.

1. 1st Post processing steps: print handles to the 3d printed surface (flexible clamping, see paragraph Flexible clamping)
2. 2nd Postprocessing steps
    a. use universal pin clamp
    b. use tooling (soft clamping).

Flexible clamping

Most 3D printed parts don't have a flat surface to mount the object onto a clamp, whereas conventional clamping could deform the shape and endanger the integrity of the object. That is why a flexible clamping system was designed. This consist of an added handle printed onto the part (see Figure 13). The goal for the flexible clamping tool is to provide an interface that can be used in a standard clamping device in the CNC machine.

Summary of the requirements:

- Flexible clamping tool must be clamped to a standard clamping device in a CNC machine, e.g. a standard vise as depicted below.

figure 11 Standard vise to clamp a block (light gray)

- The stiffness of the tool must be high enough that CNC milling process result in acceptable tolerances and surface quality.
- The interface must be easy to print and cost effective

As a result of the requirements and brainstorm in output document "O2.1 Feasibility Test" adding a handle to the 3D printed product, was the best approach.

In the picture below (see figure 12) is depicted what a handle that can be clamped in a standard-clamp looks like.

The clamp is a block with four ribs with which the clamp is connected to the product. These ribs can be adjusted in thickness in order to comply with a certain stiffness. And the overall size can be varied to suite the object's dimensions. The clamp is therefore considered to be flexible and suites the requirements for all of the user cases.

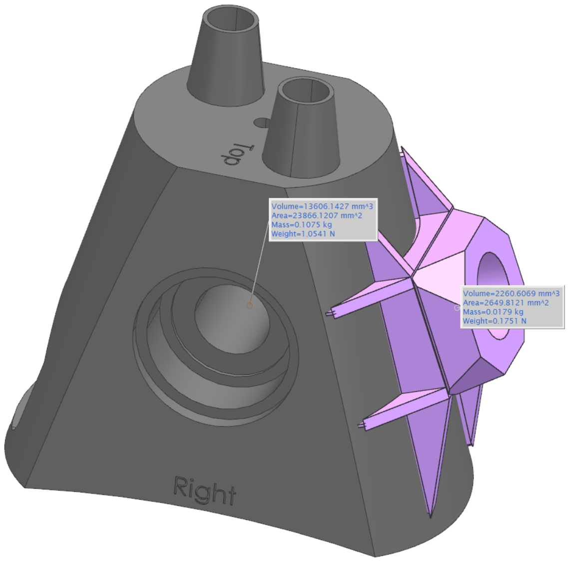


figure 12 Handle to be added to mirror object

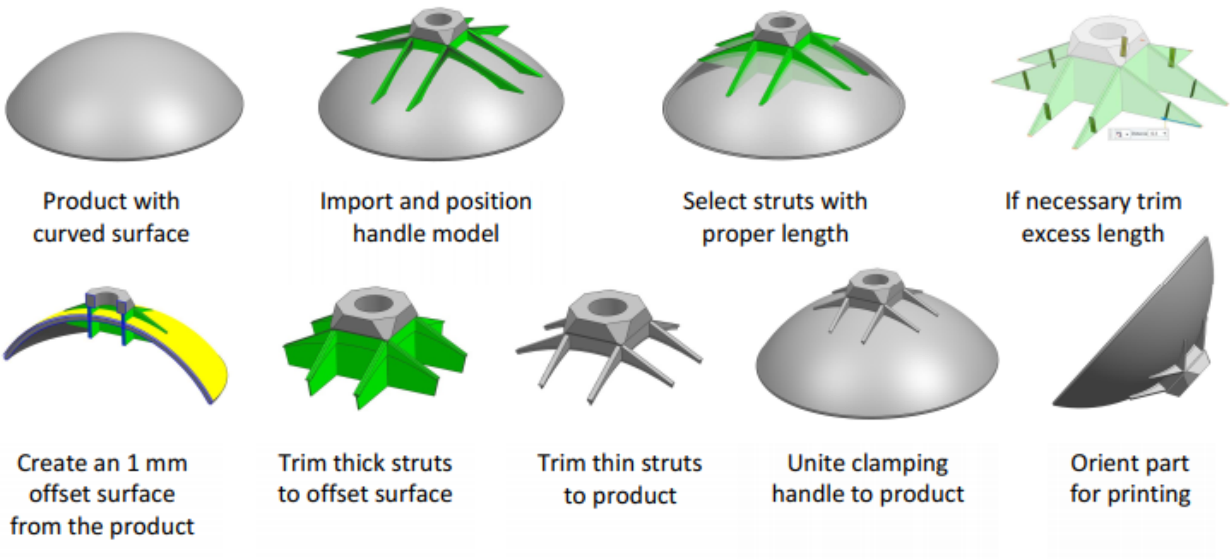


Figure 13 Examples of printed handles

4 Validation of FPP (O5)

The validation of the FPP solution was performed by executing a full-scale test and demonstration. The full-scale test was performed as a dry run test, consisting of three components:

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

This test was reported in Output report O3 Development of process and manufacture of prototype tool, available for downloading at http://www.3dfpp.eu/downloads/Output-reports/.

Because of the size and costs of the machinery involved, a industrial demonstration setup of the full process was impossible. Besides the aim of the partnership was two bring the system from TRL 3 to TRL 7, which implies that for full industrial roll-out another entity needs to bring the system from TRL 7 to TRL 9. Therefore, the 3D&FPP partnership presented the results of the research validating the FPP live on a demonstration setup using compact versions of a scanner and CNC machine. The demonstration was performed live in front of an audience on Demo Day, September 19^{th}, 2019. See the video on http://www.3dfpp.eu/downloads/Videos/.

In the validation of the FPP solution the Mirror Object serves as main research object, all other user cases will be referenced to this object.

4.1 User cases

The FPP was demonstrated with the aid of user cases stemming from different disciplines such as the maritime, automotive, cleantech and aviation industry. During the research, finding suitable user cases proved to be harder than initially anticipated. Not only are suitable objects hard to find, also the assumption parties would simply provide a user case turned out to be incorrect. Because a user case that suits the purpose of validation and has a complex shape, its design is more than often not suited for public sharing. Besides, it also appeared proper validation is more a question of qualitative analysis than quantitative. Therefore, seven user cases were defined instead of the original devised number of ten.

For validation and analysis of the FPP approach a Mirror Object was designed for research purposes only. The Mirror Object encompasses all possible design and production difficulties one could encounter in a manufacturing environment. In essence it covers all the challenges in the user cases envisioned to validate the FPP approach as a viable solution for various industries.

Each of the user cases and their respective FPP approach are described in more detail in the following paragraphs.

4.1.1 Mirror object

Drawing from experience and in close contact with relevant parties, Hittech Multin has designed the Mirror Object. This object holds every design aspect involved in 3D printing: concave, convex, tubes, holes and even an internal channel. It was designed with a high level of ambition to create an industry relevant product in every aspect.

On the Mirror Object a handle was added as flexible clamping tool to the design before 3D printing in order to be able to clamp the object after printing.

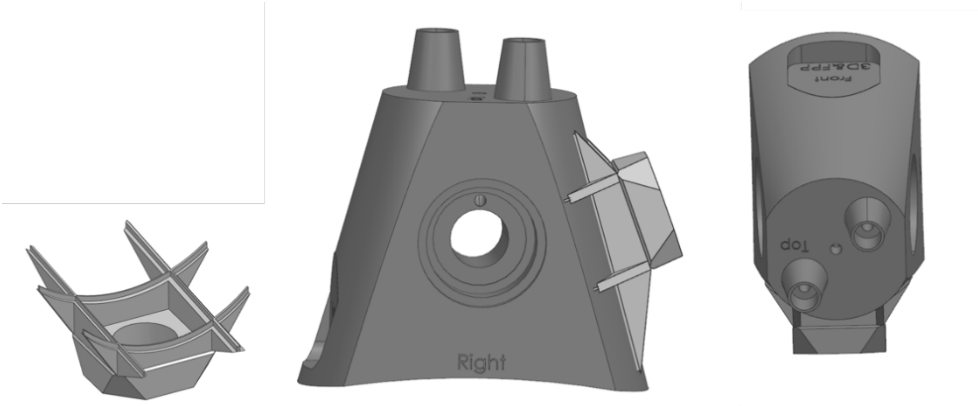


Figure 14: (left) additional handle that is added, (centre and right) mirror object with flexible clamp

While post processing, the Mirror Object was clamped on the additional printed handle. All surfaces can be processed, except for processing the surface on which the clamp is located, the so-called 6th surface. For this post processing step the Mirror Object needs to be aligned in the CNC machine (probe) to determine the offset to the final specification before milling. Hence, in order to post process all surfaces, including removal of the handle, the 6th surface of the Mirror Object needs to be post processed in a second step in which a standard soft clamp can be used.

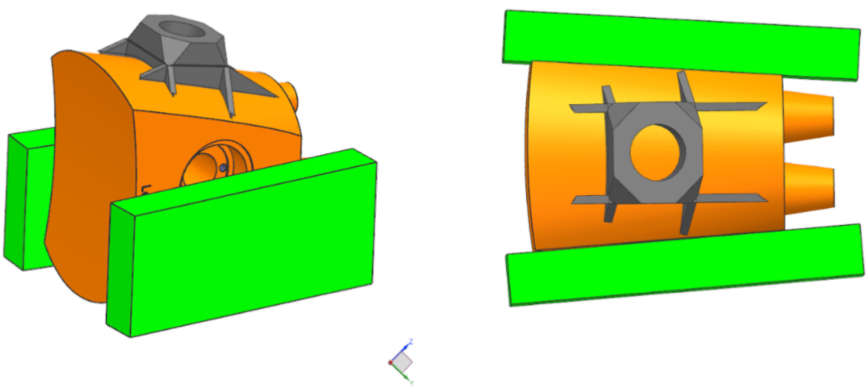


Figure 15: second post processing step in which mirror object is clamped in standard soft clamp

Since the surfaces not used for clamping are well defined as it is already post processed, it can serve as reference for the post processing of the 6th surface.

4.1.2 Hinge

Stemming from the aviation industry, Fokker provided a design for a hinge.
The hinge is a complex design with many surfaces to be post processed. The handle is designed on the bottom surface of the hinge and can be used to post process all surfaces except the bottom surface itself. For the bottom surface the hinge needs to be placed in a soft clamp. Figure 16 shows the handle for flexible clamping on the bottom of the hinge (left) and the hinge placed in tool for post processing bottom (6$^{th)}$ surface (right)

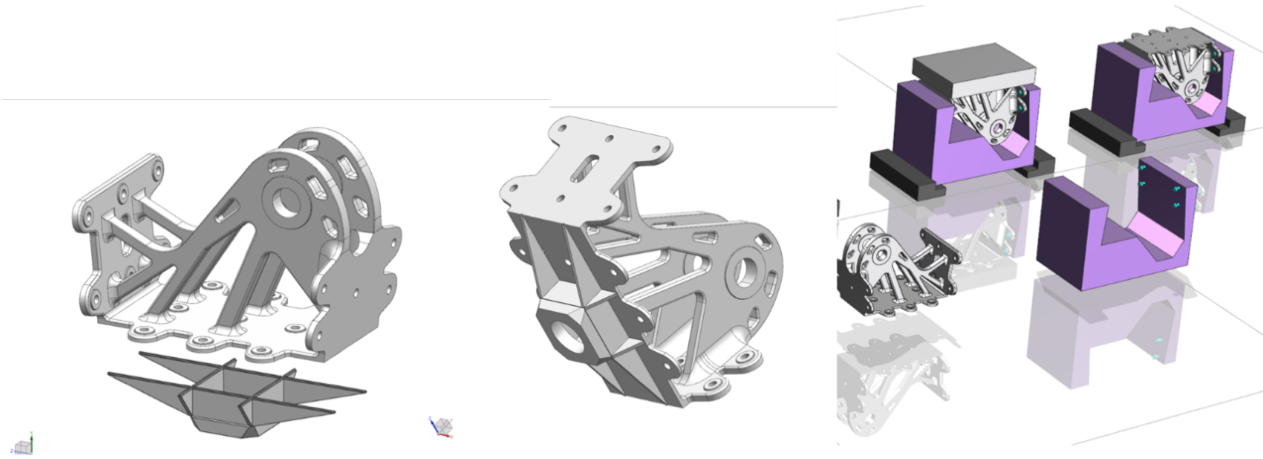


Figure 16 Hinge

4.1.3 Gearbox

Stemming from the automotive industry, TNO provided a gearbox
In the gear box design two additional handles will be printed onto the gear box, because the gear box is thin walled, see Figure 17: final gear box(left) and design for printing including support and two handles.

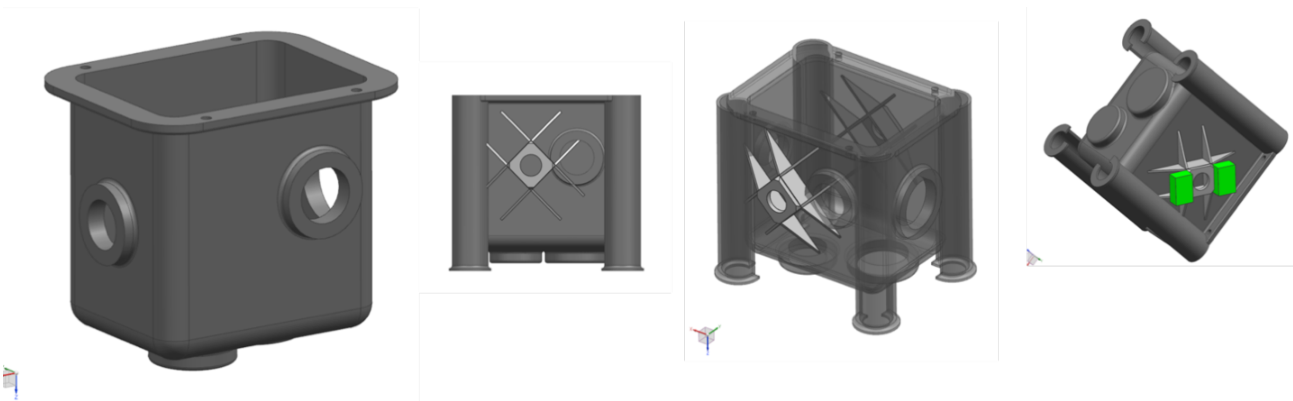


Figure 17 Gearbox handle design

For the second post processing step the gearbox is placed in a soft clamp and then the two surfaces including the handles can be post processed, see Figure 18.

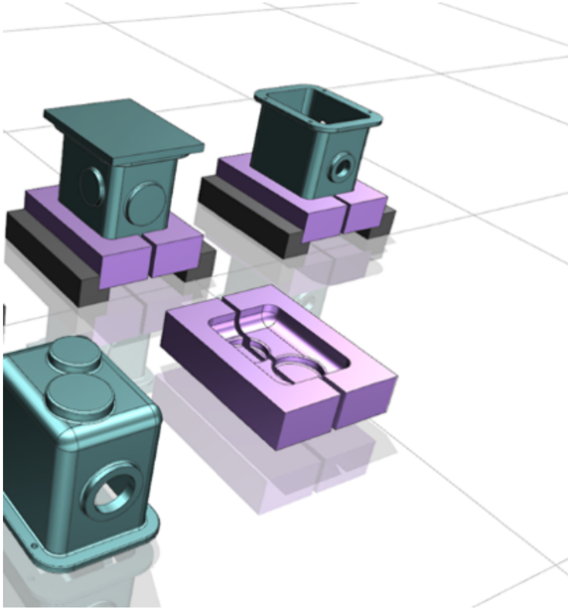


Figure 18 Gear box soft clamp

4.1.4 Cooling Core

Stemming from the promolding industry, Hittech provided a cooling core.

The cooling core is a rotational symmetric design and in order to access all surfaces it needs to be clamped in two steps. In the first step the cooling core is clamped on the cylindrical surface using as indicated in the left image. By post processing the bottom surface and the holes in the first step the surfaces are defined and can be used to clamp the cooling core in a second step, see Figure 19.

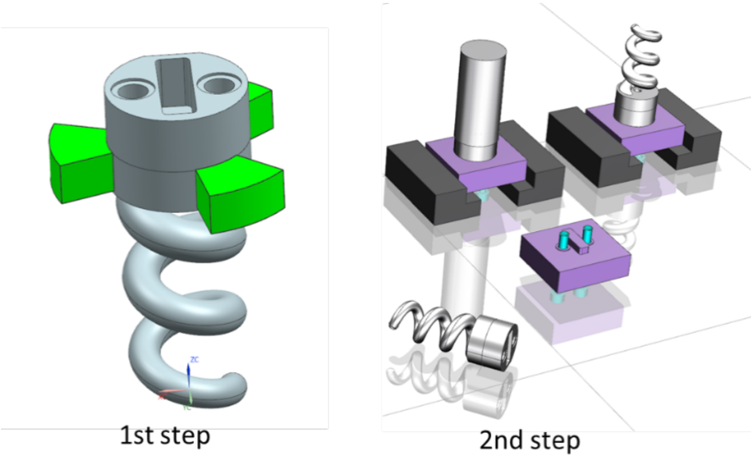


Figure 19 Cooling core clamping setup

4.1.5 Manifold

Stemming from the energy industry, Engie (B) provided a manifold.

The Engie Manifold has a thin walled structure and the tubes are long. To prevent damage due to vibrations the object needs to be supported at multiple points. A handle can be designed on the holder part and the tube can be supported by a matrix clamp, see Figure 20.

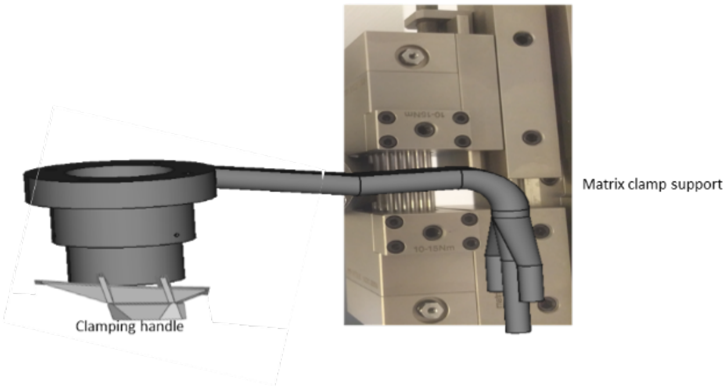


Figure 20 Manifold clamping setup

4.1.6 Propeller

Stemming from the maritime industry, RAMlab provided a mini version of a ship's propeller.

This mini propeller is similar to the 3D printed ship propeller as printed by RAMlab using WAAM and is printed in a smaller version to be used in the Aquadock, a water basin operated by the Rotterdam University of Applied Science for research and development. They are developing autonomous water drones that will be propelled by this propeller.

The surface of the propeller needs to be perfectly smooth for maximum propulsion efficiency.

The propeller is printed upside down and an extra handle is added to be able to postprocess the blades on both sides in one go. After this the handle will be cut away by wire electrical discharge machining (EDM).

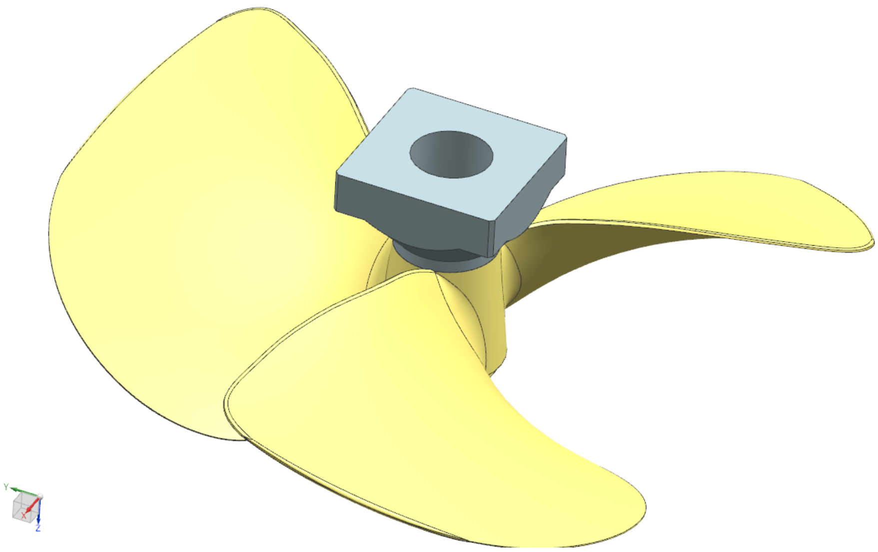


Figure 21 Propeller

4.1.7 Blade

Argon Measuring Solutions provided a turbine blade, stemming from aviation industry.
The blade needs to be printed under an angle because of the design and thin walled structures. The proposed approach is to print additional features on both ends of the object, which can be handled. These features can be clamped, and the object can be post processed. After the post processing of all surfaces the additional features can be cut away by wire EDM, see Figure 22.

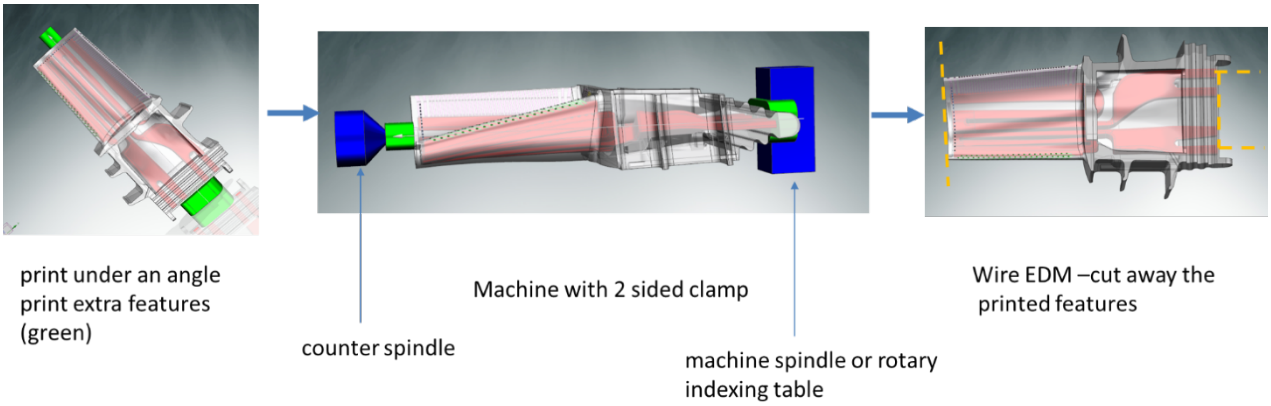


Figure 22 Turbine blade

4.2 Full-scale test

The FPP approach involves clamping, positioning, surface polishing and digitizing the interfaces between the different process steps, reducing human errors and use of expensive machining time for processes that can be executed outside of the CNC-machine.

As far as the validation of the FPP approach is concerned specifically the digitalizing of the interfaces between the different steps clamping, positioning and milling were addressed during the full-scale tests.

4.2.1 Clamping

A flexible clamp was printed as a handle to the surface of the Mirror Object. This solution provided an interface which can be used in a standard clamping device in the CNC machine, and had to meet three criteria.

1. The clamp must be rigid enough to allow for meeting geometric tolerances and defined surface quality.
2. The clamp must be added cost effectively.
3. The clamp is adapted to conventional clamping systems.

As a result of these requirements and as described in output document O.2.1 Feasibility test the added handle or clamp as depicted in figure 12 was developed.

4.2.2 Positioning

In order to facilitate the positioning of printed parts onto a CNC machine, 3D scanning technology was applied to obtain the digital model of a complete part which could be compared to the original CAD model to find the relationship between the part's real position and its theoretical position designed in the CAM program.

This relationship represented as a Coordinate System Transformation Matrix (CSTM) can subsequently be used for the modification of the NC-code to perform the post-machining according to the part's real clamping position.
The algorithms for comparing the original CAD model and scanned model generate the CSTM. Moreover, the approaches of integration with the CNC system, were investigated, developed and validated.
Based on the developed model comparison algorithms and the CNC integration approaches, an online integration software tool has been developed called the Compiler. With this online tool the CSTM to modify the NC-code can be generated.

4.2.3 Polishing

The results of polishing and roughness reduction highly depends on the shape, material and initial roughness of the product. After the milling process conform to the FPP approach the Mirror Object was submitted to a generic polishing treatment. The aim was to reduce the surface roughness from Ra = 1.6 (standard for milled surfaces) to Ra = 0.4, while keeping the object geometry within specs.

Both specs regarding surface roughness and geometry were met. It must be noted a generic approach on polishing with respect to the FPP approach could not be given. Too many factors, like the shape of the object, material use, surface specifications and prescribed geometry tolerances affect the choice of surface treatment technology.

Laser polishing was part of the overall assessment of polishing technologies available and able to be integrated. The maturity of this specific technology is not there yet, nor is the accessibility of the technology. Laser polishing was therefore not further evaluated as an alternative solution for the FPP approach. Hence, the choice for surface treatment will continue to be the outcome of surface specifications, use of material, geometry tolerances, available polishing technologies and their respective cost trade-offs.

4.3 Demonstration

On September 19th, 2019, the 3D&FPP partnership presented the results of their research into integrating 3D metal printing and flexible post-processing with a live demonstration of the full setup including the algorithm.

Because of the size and costs of the machinery involved, a full scale demonstration of the process is impossible. Instead, the 3D&FPP partnership presented the results of the research validating the FPP live on a demonstration setup using compact versions of a scanner and CNC machine. This setup will also be available for dissemination purposes after the 3D&FPP project ends. The demonstration model consists of machines (3D printer, 3D scanner and pocket NC), model objects (end results and testing objects) and visualization (overall process) on screen.

4.3.1 Demonstration Setup

The demonstration setup was selected after market research of available equipment meeting the requirements for demonstration and able to handle the FPP. The recommended 3D scanner is the Shining 3D Einscan because it meets the requirements of the scan speed, price, accuracy (0,1 mm) and resolution. It is able to handle objects up and until 200x200x200 mm. The Einscan also has a turntable and is the most user friendly (see Figure 23).

Figure 23 3D scanner

As milling machine, the pocket NC was recommended because of the reliable quality, shortest delivery time and low price quality ratio. The pocket NC is connected to a computer with a web-interface showing the controls of the pocket NC, see Figure 24.

Resolution:

- x,y,z-axis: 0.00024 inch
- a,b-axis: 0.01degree

The Pocket NC is controlled by BeagleBone Black running Machinekit/Rockhopper and Autodesk Fusion360, post processor is included.

Figure 24 Pocket NC

Besides the scanner and milling machine, a couple of demo objects selected from the user cases were needed showing the printed version and the post-processed version. The demo object, like the hinge as shown in figure 24, is bolted on the standard clamp, in a purposefully 45 degree 'wrong' angle.

The adjustment of the G-code was shown on screen. It showed two processing files:

- the original one, which assumes that the demo object is placed perfectly straight
- the compiled one, with the applied transformation

4.3.2 Positioning and orientation

As stated earlier, as soon as a 3D printed object is removed from a 3D printer, all information concerning its shape and orientation is lost. To this end the 3D printed part is first placed onto a clamp. For demonstration purposes the part was deliberately placed in a 45-degree false angle. In real production processes this error would be in the range of 0.1 degree. The FPP approach will treat a minor offset the same way as it treats a major offset.

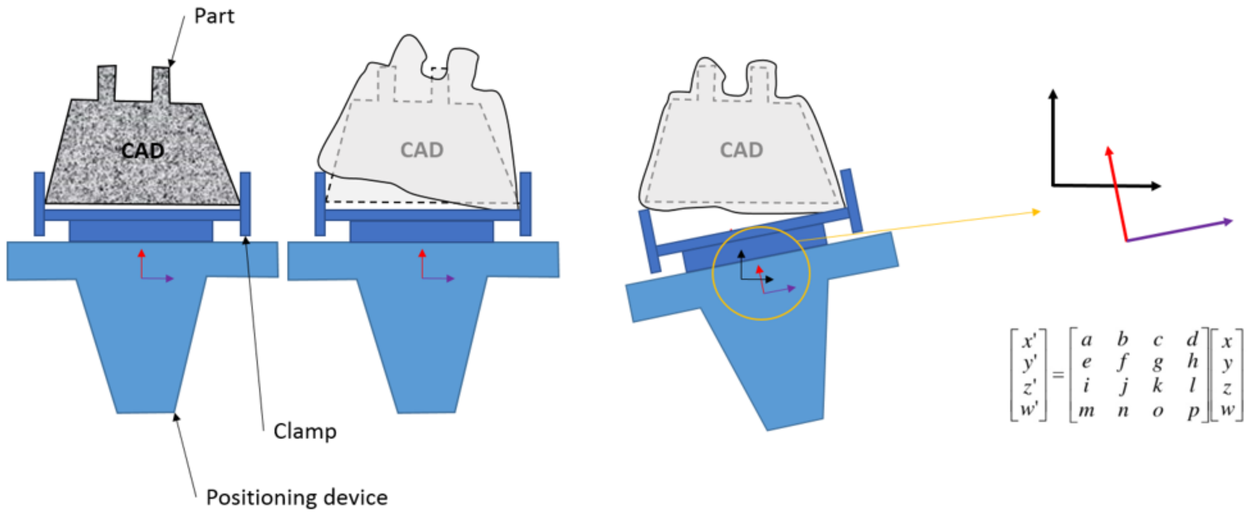
After the part is mounted onto the clamp, both the clamp and the printed object are scanned. In this case the object was bolted onto the clamp, which was the best option to do it given the parts geometry.

Using a standard clamp, post processing of five sides of the object is easily achieved.
If the sixth surface also needs post processing, in effect removal of the added handle, a soft clamp needs to be designed.

For positioning purposes, the object is scanned. The demo setup uses GOM software to analyse the scan data by comparing the scan with the original CAD file. This comparison shows two things:

1. The actual orientation of the clamped 3D printed part and the transformation that is needed to go from a perfectly aligned part to the actual alignment.
2. Whether the 3D printed part has enough stock material on the surfaces that need to be post processed.

See Figure 25



$$\begin{bmatrix} x' \\ y' \\ z' \\ w' \end{bmatrix} = \begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$

Figure 25 Definition of position and stock

At this point misprints can be excluded from the post processing process, saving handling time and machining hours.

Conventionally the scan process will be done in an expensive 5-axis milling machine by an operator, using a touch probe. Given de roughness of a 3D printed part this is a time-intensive process. On top of that, it lacks accuracy for it only provides information about the points that are measured. Besides, during this measurement the 5 axis CNC milling machine sits idle, which translates into incurred opportunity costs.

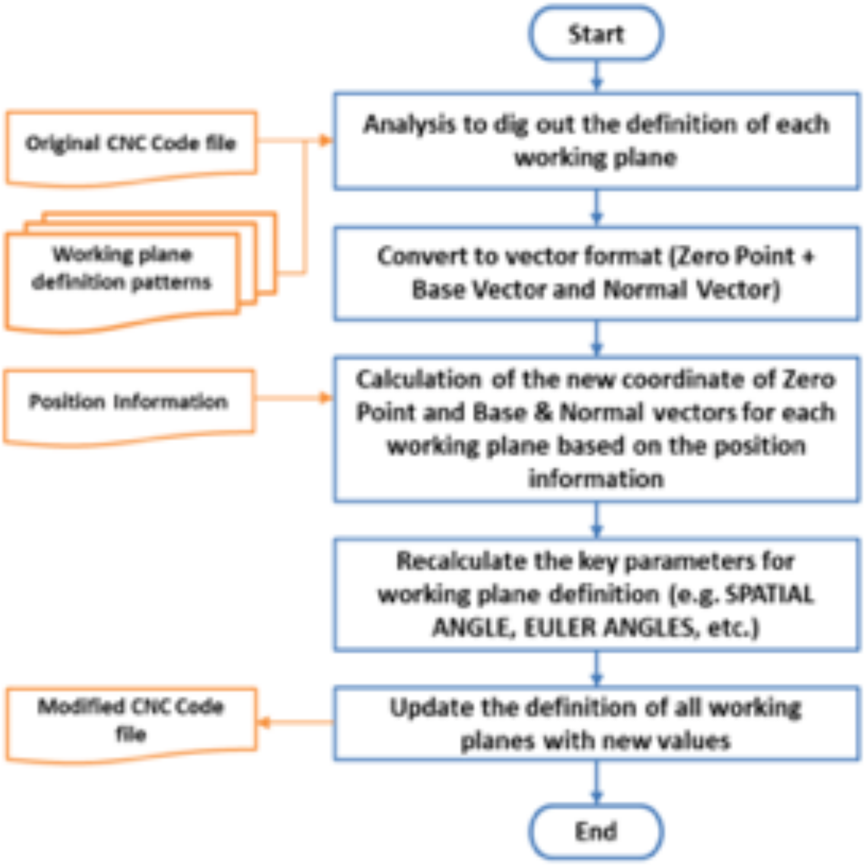


Figure 26 Flowchart modifying NC code

4.3.3 Use of the Compiler

As the object was designed and the CAD-file provided to the 3D printing company, a suitable location for the handle is defined and stock material added to the surfaces to allow for post processing. Subsequently a CAM programmer provides the NC-code for the post processing steps. This code tells the 5-axis CNC milling machine which paths and tools to use. Programming this code is a labour and time-intensive process. That is why it is done in parallel with the printing process.
This NC-code is based on a perfectly aligned object. This NC code is therefore adjusted by the compiler for the real or actual position of the part in the milling machine, based on the acquired scan data.

This process of converting the NC-code is fully automated in the online Compiler, see Figure 27.

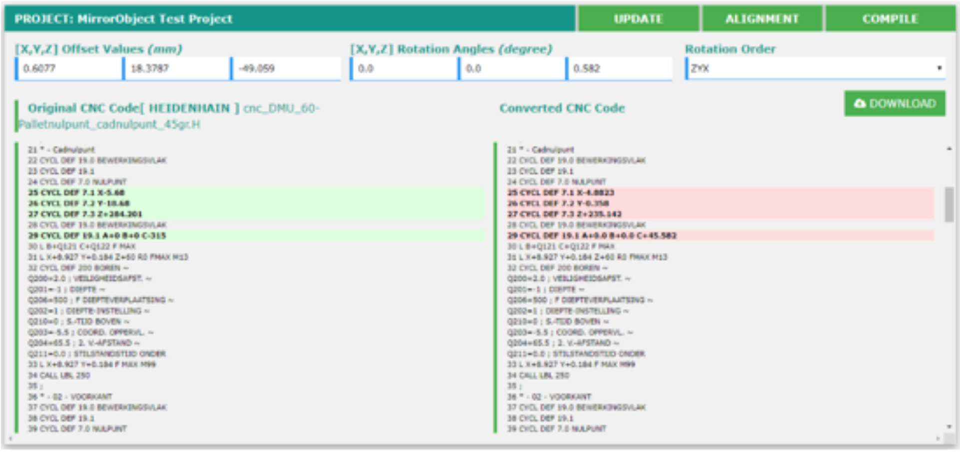


Figure 27 Input and output of NC compiler

The converted/adjusted NC code can now be downloaded and used to instantly mill the part in the CNC machine without any additional handling or positioning efforts. Again, saving valuable machine and operator's time.

4.3.4 Considerations Demonstration Setup

Use of material

For demonstration purposes only plastic prints were used for the demo only shows the process of the FPP approach. Besides, plastic prints are much cheaper than metal prints. More importantly, the post processing of plastic prints is much safer than metal prints. Metal parts can chip off during the process, which could endanger people watching the process.

Use of a standard clamp

There are no industry-grade standard clamps available like the Erowa Clamp that could be used in the pocket NC. That is why we choose the hinge as the demonstrator object, which could be bolted onto a standard piece of worktable.

Deviant machine control

There is no tabletop CNC machine available in the market with similar machine control as the industrial milling machines, on which the Compiler algorithm is based. However, lot of effort is given to ensure the current demo setup does adequately show all the process steps that would be taken in an industrial environment.

All these considerations and corresponding choices have been made carefully to simplify the process without diminishing the credibility of the Demo Setup.

4.4 Technical and economic validation

Available data on 3D printing and post-processing of 3D printed parts are used to provide a framework for calculating time and cost-savings related to implementation of 3D&FPP algorithm. Information from 3D&FPP Project partners has been used and combined with data from open sources and university databases.

A lot of factors influence the cost and time reduction achieved by flexible post-processing. Some of these factors are universal. For instance, the cost of- and time associated with programming the product, designing the product, material costs, 3D production, quality control, measurements, clamping, machine adjustments, machining and polishing all have influence on the cost and time savings.

However, other factors depend on the type of product, the products requirements and production setting. For instance, the type of material used, the need for internal support structures or cooling channels affect the variables in cost/time reduction. Furthermore, depending on the products' required specifications, different clamping methods or post-processing approaches have to be used in order to accurately calculate the time and cost reduction that will be achieved. The level of irregularity of factors influencing the calculation makes creating a complete universal cost and time reduction assessment unrealistic.

In order to gauge the cost and time savings, a rudimentary assessment of applicability of the FPP approach has been composed, taking into account manufacturers production specifics. In addition to this calculation format, further in-depth calculations will have to be made on a product-specific basis (taking into account the previously mentioned factors) in order to come up with a definitive conclusion per product, product family and manufacturing settings.

A last important factor that influences the cost calculation is the batch size of production. Some costs like design cost are made once and are independent of the amount of the same products that are made. These costs are "one off costs" that are incurred once and can be divided over the total amount of products to be made. The second group of costs are related to each individual product that is made for instance material costs, printing or milling cost. These are "per part costs" and are attributed to each product independent of the total amount of products that is made. The individual cost price per product is determined by the "one off cost" (divided by the batch size) and the "per part cost".

In the cost determination model the cost of individual steps in the process are analysed and is used to determine the overall cost. This is done for both the conventional process as well as the 3D&FPP process. The activities considered are:

- Generation of AM CAD design,
- 3D printing,
- Positioning and measurement,
- Postprocessing and
- Quality/logistics.

After the postprocessing steps both the conventional and FPP process are similar and the incurred costs there are the same and therefore all additional steps are grouped as one cost group.
In all these activities the costs can be either labour, material or machine cost or combinations thereof, expect for one cost item, namely opportunity costs. In the conventional process the object is measured and positioned inside a CNC machine multiple times. During this time the CNC machine cannot be used for other products. When other objects are made or processed on the CNC machine this results in products that can be sold with a profit margin. This loss in productivity is considered as additional costs incurred.

4.4.1 Considerations

Since a model is always only a representation of the reality some aspects need to be considered. This results in the following assumptions.

1. In the FPP process an additional clamp can be added to the design. It is assumed that this clamp will not result in increased failure rate of the 3D printed object.
2. In conventional production processes multiple post processing steps with individual clamping solutions are needed. It is assumed that the first step will be done with the printed clamp and only one final step with a separate clamp is needed.
3. The interface of the machines used are pre-aligned and scanned and the machines used for post processing are used for many products. This results in the cost of this process being negligible for both the conventional as well as the FPP process.
4. In case the object is positioned and measured in the CNC machine, this uses valuable machine time during which the CNC machine is not available for things and this is considered opportunity costs.
5. FPP does not affect the 3D printing process. 3D printing an object (the 3D printed clamp excluded) therefore results in the same failures rates. The difference is that during FPP, the rejects are determined directly after scanning the object instead of after post processing. This avoids post processing of bad parts, hence reducing costs and lead time.
6. After the final postprocessing step, the downstream process of e.g. quality control and logistics is considered to be the same and no further specification for conventional postprocessing and FPP is made.

4.4.2 Cost and time reduction

Using the assumptions as stated in §4.4.1, a model has been drawn up to execute the calculations on the use cases. The various input for the calculations was based on the expertise of the project partners.
In the model expected batch sizes can be entered, calculating production costs. The final cost comparison is presented as function of batch size.
For the use case the results are given in the following graphs and table 1.

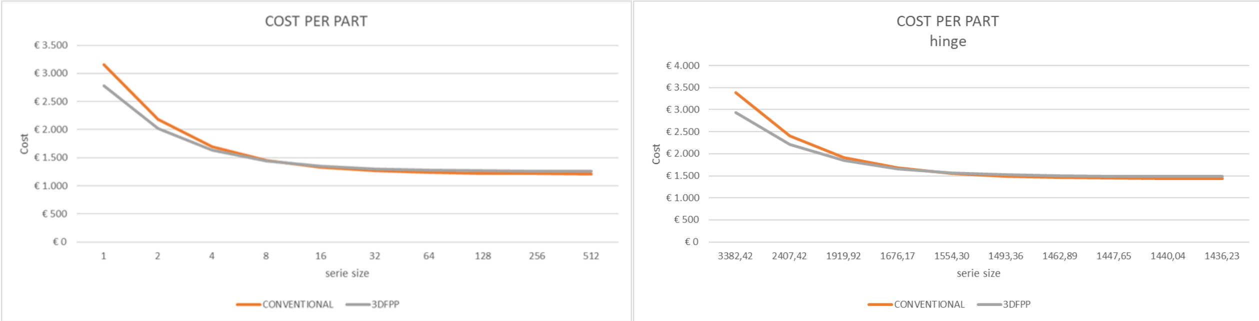


Figure 28 Cost analysis of Mirror object and hinge

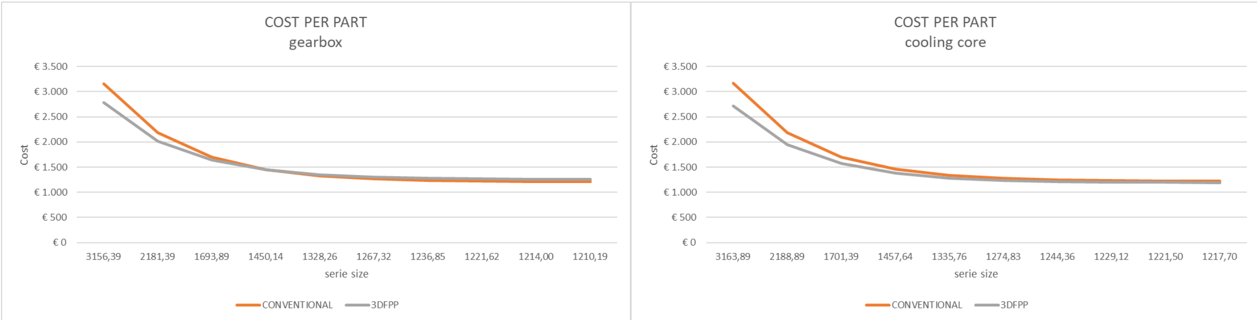


Figure 29 Cost analysis of gearbox and cooling core

Figure 30 Cost analysis of Engie manifold and propeller

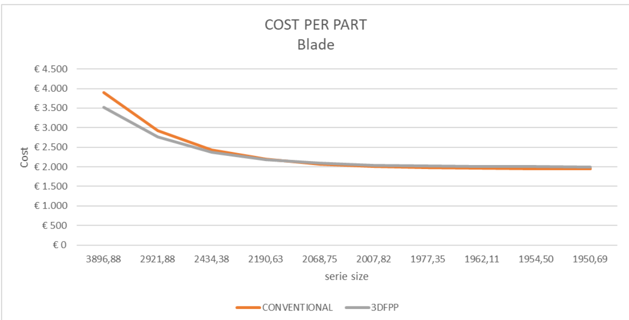


Figure 31 Cost analysis of blade

Table 1 Cost comparison of use cases

	BATCH SIZE									
mirror object	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	3156,39	2181,39	1693,89	1450,14	1328,26	1267,32	1236,85	1221,62	1214,00	1210,19
3DFPP	2779,83	2017,33	1636,08	1445,46	1350,15	1302,49	1278,66	1266,75	1260,79	1257,81
saving	14%	8%	4%	0%	-2%	-3%	-3%	-4%	-4%	-4%
hinge	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	3382,42	2407,42	1919,92	1676,17	1554,30	1493,36	1462,89	1447,65	1440,04	1436,23
3DFPP	2937,44	2207,94	1843,19	1660,81	1569,62	1524,03	1501,23	1489,83	1484,14	1481,29
saving	15%	9%	4%	1%	-1%	-2%	-3%	-3%	-3%	-3%
gearbox	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	3923,89	2948,89	2461,39	2217,64	2095,77	2034,83	2004,36	1989,13	1981,51	1977,70
3DFPP	3549,70	2787,20	2405,95	2215,33	2120,01	2072,36	2048,53	2036,62	2030,66	2027,68
saving	11%	6%	2%	0%	-1%	-2%	-2%	-2%	-2%	-2%
cooling core	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	3163,89	2188,89	1701,39	1457,64	1335,76	1274,83	1244,36	1229,12	1221,50	1217,70
3DFPP	2713,35	1950,85	1569,60	1378,97	1283,66	1236,00	1212,18	1200,26	1194,31	1191,33
saving	17%	12%	8%	6%	4%	3%	3%	2%	2%	2%
Engie manifold	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	3444,08	2469,08	1981,58	1737,83	1615,96	1555,02	1524,55	1509,32	1501,70	1497,89
3DFPP	3035,52	2273,02	1891,77	1701,14	1605,83	1558,18	1534,35	1522,43	1516,48	1513,50
saving	13%	9%	5%	2%	1%	0%	-1%	-1%	-1%	-1%
propeller	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	5250,38	4275,38	3787,88	3544,13	3422,25	3361,32	3330,85	3315,61	3307,99	3304,19
3DFPP	4971,21	4208,71	3827,46	3636,83	3541,52	3493,86	3470,03	3458,12	3452,16	3449,18
saving	6%	2%	-1%	-3%	-3%	-4%	-4%	-4%	-4%	-4%
blade	1	2	4	8	16	32	64	128	256	512
CONVENTIONAL	3896,88	2921,88	2434,38	2190,63	2068,75	2007,82	1977,35	1962,11	1954,50	1950,69
3DFPP	3520,75	2758,25	2377,00	2186,38	2091,06	2043,41	2019,58	2007,67	2001,71	1998,73
saving	11%	6%	2%	0%	-1%	-2%	-2%	-2%	-2%	-2%

As shown in table 1 the cost reduction for the uses cases vary from 6 to 17% for a single product. The propeller has a lower cost reduction than the others with 6% and this is due to the volume of the object, where the effect of material cost and print time are more dominant wrt post processing. These cost reductions are based on total cost, when looking at the postprocessing part only the effect of the 3DFPP process is more clear, where the case of a single object is used.

Table 2 Cost comparison for total cost and post processing only for a single object

	cost					
	total			postprocess		
	conv	3DFPP	dif(%)	conv	3DFPP	dif(%)
mirror	€ 3.156	€ 2.780	14%	€ 2.345	€ 1.862	26%
hinge	€ 3.382	€ 2.937	15%	€ 2.412	€ 1.868	29%
gearbox	€ 3.924	€ 3.550	11%	€ 2.572	€ 2.038	26%
cooling core	€ 3.164	€ 2.713	17%	€ 2.347	€ 1.806	30%
engie manifold	€ 3.444	€ 3.036	13%	€ 2.430	€ 1.895	28%
propeller	€ 5.250	€ 4.971	6%	€ 2.965	€ 2.433	22%
blade	€ 3.897	€ 3.521	11%	€ 2.564	€ 2.030	26%

Regarding the aspect of lead time the process is similar to conventional and for FPP except for two distinct differences that influence the lead time:

1. The postprocessing is done in less steps, so handling and repositioning of the object is reduced. The associated gain in costs depends on the complexity of the part involved.
2. The second effect is that failed objects are detected right after the 3D scanning, in contrast to conventional post processing, failed objects are detected after completion of post processing. This is the case for approximately 15% of the objects. The postprocessing is considered to be half of the total lead time.

So, in 15% of the objects the lead time is reduced by half, resulting in a total lead time reduction of 7,5%.

The full calculation model can be found in Annex A and at http://www.3dfpp.eu/downloads/Tools/

A comparison of the complexities of the different use case is given in Table 2 and the factsheets in Annex B.

Table 3 Cost comparison user cases

User Case	**Characteristics compared to Mirror object**	**Increase/Reduce costs**
Aircraft Hinge	Hollow struts instead of internal channels.	Less material use which reduces costs. Possibly more print support structure needed which increases costs (should be designed to avoid needing internal support structures)
	Holes in the struts requiring post-processing.	Might increase costs
	Narrow spaces tend to be filled with sintered powder. This is challenging to remove after printing	Increases costs (not necessarily)
Overall	Overall complexity = equal	Cost neutral
Gear Box	Does not require re-clamping for post-processing	Reduced costs
	Holes will be milled/drilled after printing and are printed closed.	Increases costs (same as mirror object) cost neutral
Overall	Overall complexity = less complex	Reduce costs

Cooling Core	Smooth surface according to industry standards	Might increase costs (same as mirror object) cost neutral
	Requires positioning interfaces with less tight tolerances.	Might reduce costs
	Positioning and air relieve slits by fitting tolerances.	Might increase costs
	Wall thickness should be able to withstand 1000 Bar pressure.	Increase costs (should not change the costs as that is incorporated into design)
Overall	Overall complexity = equal	Cost neutral
Manifold	Thin walled structures	Less material use which reduces costs Possibly more print support structure needed which increase costs
	Long thin channels which are sensitive to vibrations during processing	Clamp will have to meet special needs, increase costs
	Long channel section has no obvious way for clamping	Special design for clamp needed which increase costs
Overall	Overall complexity = less complex	Reduce costs
Propeller	Three dimensional curved surfaces.	Difficult for the milling process might increase costs
	Surface roughness has to be perfectly smooth for maximum propulsion efficiency.	Will set certain standard for polishing, but not necessarily increase costs → Not "higher" standard but relative more surface area and complex shape
	Large volume	The large volume will increase the relative cost of the material and printing and reduce the relative gain in the post processing
Overall	Overall complexity = equal	Cost increased
Blade	Thin walled structures	Less material use which reduces costs Possibly more print support structure needed which increase costs
	Smooth surface finishing required	Will set certain standard for finishing, but not necessarily increase costs same as propeller
	Stable shape easy to clamp	Reduced costs
Overall	Overall complexity = equal	Cost neutral

5 3D&FPP: conclusion, reflection and future

The 3D&FPP project aimed to develop an innovative, knowledge and research based, sustainable, flexible, efficient and affordable retrofit post processing solution. The projects' goal was to design a process that works as an add-on to existing machines. This implied four main production processes need to be integrated: clamping, scanning, polishing and CAD/CAM-systems.

The partnership developed a Flexible Post Processing solution (FPP) able to locate and map the object, establish and translate the required post processing steps with a minimum of re-clamping and repositioning actions. FPP consists of a validated algorithm embedded in a cloud-based compiler able to map the object and its orientation, calculate the transformation matrix and adjust the NC-code in order to mill the object into its net shape.

5.1 Conclusion

The FPP solution was successfully validated and demonstrated using user cases.
From the cost calculation model, it is determined that for the Mirror Object the cost reduction is 26% on the total costs and 15% on the postprocessing.

As the project was aimed at a cost reduction of 30%, the achieved reduction of 26% for post processing only is an important and significant improvement.
The project also aimed for 50% reduction in production time. The achieved lead time improvement is 7,5%, which is significantly lower. However, in the field of 3D printing 7,5% is considered an important lead time improvement.

The FPP approach is a viable and validated way of work at Technology Readiness Level 7 (TRL). Its contribution to a more cost and time efficient process highly depends on the type of product, the products requirements and manufacturer specific production settings. The calculation model developed by the 3D&FPP partnership will serve as a tool for manufacturers to assess the applicability of the FPP approach taking into account all their production specifics which impact the costs and time savings implied.

5.1.1 Feasibility

The FPP solution encompasses existing technology that can be integrated, making post processing an inexpensive and time efficient activity. The validation tests of the FPP approach showed the suggested solution fulfill the requirements for industrial high precision application and the solution is generic for it supports the three main operating systems currently dominating the industry (Heidenhain, Fanuc and Siemens). Since existing machines have a typical lifespan of 10-15 years, the project has a significant impact in the short term.

5.1.2 Technology readiness

According to EU's Horizon 2020 description, the Technology Readiness Level (TRL) is described as follows:

- TRL6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 7 – system prototype demonstration in operational environment.

The flexible postprocessing solution was successfully demonstrated in an operational environment during Demo Day on September 19^{th}, 2019.

Based on this description the (TRL) of the FPP progressed from 6 to 7.

The FPP approach as a retrofit has the potential to facilitate innovation in the high precision industry, enabling capitalisation on the possibilities 3D metal printing technology is offering.

5.2 Reflection

The 3D&FPP project was committed to integrate existing technologies into a generic, inexpensive and time efficient production process. As far as integration is concerned, the FPP approach has shown integration by the digitalizing of the interfaces between the different steps clamping, positioning and milling is feasible.

A generic prediction of the assumed cost and time savings associated with the FPP approach could not be given, due to the complexity of the production processes involved, the (family of) object(s), materials and batch sizes.

A carefully drafted calculation model based on the insights from the FPP approach and taken into account all possible production specifics enables further assessment by manufacturers of the applicability of the FPP approach in their own commercial environments.

5.3 Future developments

As the FPP approach is to be considered as TRL 7, further development of the solution is needed. In the development of the FPP from TRL 7 to TRL 10, two major items are subject for further research.

1. Is the FPP approach on the level of a single manufacturer to be considered as a product of a service?
2. What are the main obstacles hindering the introduction in existing 3D printing markets.

These subjects are addressed in more detail in the next paragraphs.

5.3.1 Technology Readiness

The 3D&FPP project delivers the FPP solution on a TRL 7, meaning this is not a market ready product yet. Considering all of the above, future development will mainly be focused on how to adjust processes and procedures to facilitate the use of the FPP approach in order to fully benefit from the costs and time savings implied. When applied, this will bring the FPP approach from TRL 7 to 10.

5.3.2 FPP as a product or as-a-service

Commercially, Flexible Post Processing has not only the potential of being offered as a product but also as a service.

An example of a product is a software package, based on which interested parties should determine if they could benefit from retrofitting machines with FPP - for example, when lead time is of their interest (e.g. racing teams, airports, ships). Additionally, software development companies, who are in collaboration with CNC machine producers, could enable development of machines with FPP in mind.

FPP 'as-a-service', an offering could be created by assembling specialised companies (3D printing, scanning, milling and post-processing) into a collaboration and create a hub which could derive a competitive advantage of speed and/or price from using FPP throughout its chain.

All these ideas could be investigated and expanded on by the 3D&FPP partners or by outside parties with potential cooperation or consultancy possibilities from the project partners.

5.3.3 Challenges related to implementation

A lot of factors influence the implementation of flexible post-processing.

Besides the way the FPP is considered (as a product or as a service) and given current TRL (7), several issues can be identified as potentially hindering implementation in manufacturing processes. Main factors affecting smooth implementation are:

- Machine incompatibility with software (compiler).
  The FPP supports the three main operating systems currently dominating the industry (Heidenhain, Fanuk and Siemens). If, however, a manufacturer does not have those machines at their disposal, it hinders implementation of the FPP solution as is. As a result, having compatible machinery and software is a condition to implementing FPP rather than a problem.
- Designing in compliance with FPP process.
  The FPP approach also affects the way an object is designed, for it will need to have the proper support structures whilst printing and a flexible clamping tool for the post processing steps[2]. This implies coordination between the CAD design and post processing steps.
- Increase collaboration between departments.
  Flexible post-processing calls for increased cooperation and coordination between the production and post-processing staff within organisations. This can potentially cause problems as they originally functioned as two separate "departments" or entities, and now are part of a new, single production chain
- (Re-)training of staff.
  Any new approach requires a certain degree of training. This training addresses both learning the process and learning to collaborate.
- Timing of implementation.
  It is of utmost importance that organisations take the time for implementation, to make sure the organisation is completely ready to use the new technology on customer parts. Personnel as well as the organisation itself need to have the time to adjust to new regimes and procedures. If the implementation is rushed, the likelihood of problems occurring after the implementation increases significantly.

[2] This is well illustrated by the fact that in traditional manufacturing, making a hole costs money, whereas in additive manufacturing, it is free. (Quote of mr. Bentley, 3T AM)

Annex A Calculation Model

The calculation sheet is also available for downloading at http://www.3dfpp.eu/downloads/Tools/ .

Annex B Factsheets validation user cases

The following factsheets depict the overall features of the various user cases set against the object functionalities and criteria of Mirror Object. These comparisons give an insight in the difficulties and uniqueness of the user cases, applicability of the FPP approach and consequences for the reduction in production time and costs. The absolute figures on the cost savings as implied can be calculated using the calculation sheet as provided at http://www.3dfpp.eu/downloads/Tools/ .