HORIZON 2020

REQUIREMENTS: PROCESS PLANNING FOR AM

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EXECUTIVE SUMMARY

The scope of this document is to summarise the main requirements of Process Planning (PP) in Additive Manufacturing (AM), with specific reference to the CAxMan design-simulation-manufacturing workflow.

Firstly, a literature analysis was performed to investigate the main steps of PP and how they have been approached in existing studies. Then, the baseline of AM PP is described according to the method used by the project partner Tronrud, who will implement the manufactured metal parts for the project use cases. The requirements of PP were investigated also with reference to AM of plastic parts, showing several similarities to the problem being investigated. A survey among the main stakeholders of the CAxMan design-simulation-manufacturing workflow allowed summarising the key aspects that should be taken into account in the development of the PP algorithms. Some details on the available AM machine are provided together with an analysis of the options concerning the process parameters editing. This is particularly relevant because a lot of optimization loops cannot be implemented if the machine parameters cannot be edited.

Finally, a summary of the main requirements of the PP in CAxMan is reported, together with an overview of the PP Tasks.

TABLE OF CONTENTS

1 INTRODUCTION

Process planning is concerned with determining the sequence of individual manufacturing operations needed to produce a given part or product. The resulting operation sequence is documented on a form typically referred to as a route sheet (also called as process sheet or method sheet) containing a listing of the production operations and associated machine tools for a work part or assembly.

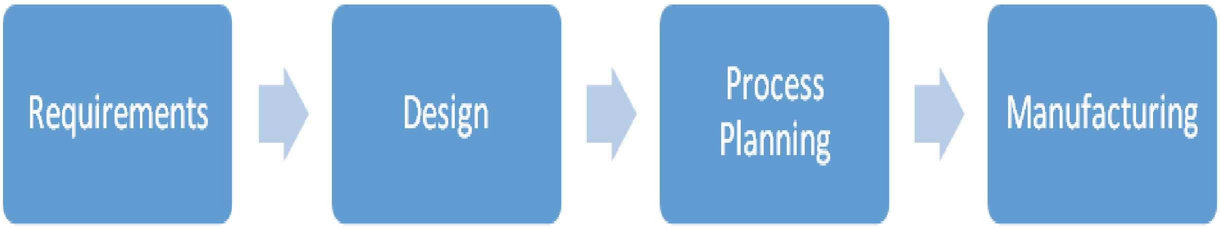

FIGURE 1: PART DEVELOPMENT WORKFLOW

Within a general Part Development Workflow (Figure 1), PP takes the designed part as an input and generates the set of information required to manufacture it, e.g. the toolpath, the process parameters, etc. Since CAxMan addresses AM technologies, the requirements collected in this document refer to these manufacturing techniques only.

Nowadays, the main AM technologies can be broadly categorised according to the deposition method used:

- Extrusion
- Light polymerized
- Powder Bed

The project partner Tronrud plans to implement the manufactured demonstrators for CAxMan Use Cases using an EOS M280 3D Printer, which uses a powder bed technology. Hence, the present document as well as CAxMan WP3 will focus on powder bed technologies, with particular reference to: Selective laser melting (SLM), Selective laser sintering (SLS) and Direct Metal Laser Sintering (DMLS).

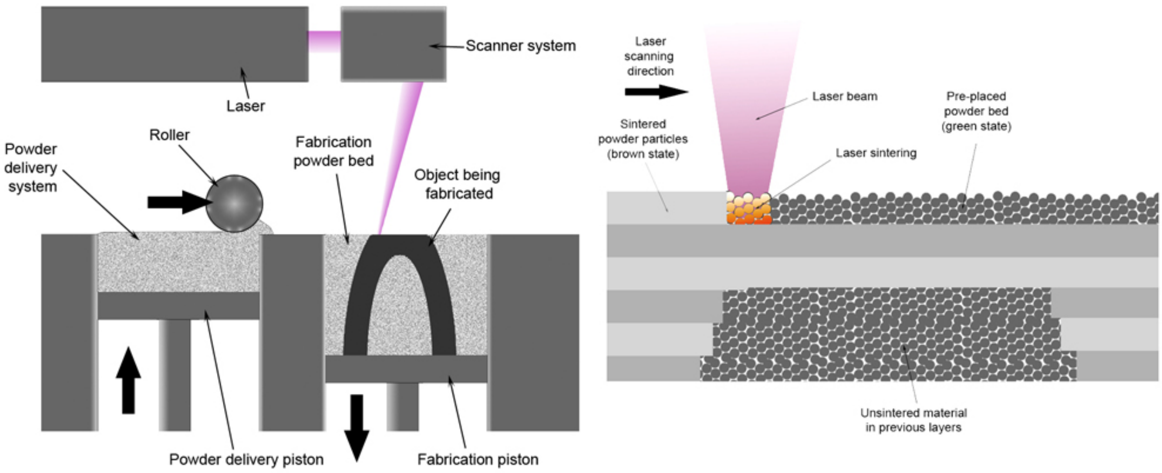

FIGURE 2: SELECTIVE LASER SINTERING PROCESS (IMAGE COURTESY OF WIKIPEDIA)

All of them are additive manufacturing processes that use 3D geometric data as a digital information source and energy in the form of a high-power laser beam, to create three-dimensional metal parts by melting or sintering fine metal powders together. As in many other additive manufacturing processes, the part to be manufactured is built up from many thin cross sections of the 3D model: a thin layer of powder is spread across the completed section and the process is repeated with each layer adhering to the last. When the model is complete, unbound powder is removed and may be reused. In all the three processes, the object is built up layer by layer by a laser which selectively melts the upper layer in a powder bed (Figure 2). The whole process is performed in a build chamber filled with an inert gas.

SLM and DMLS are essentially the same thing, with SLM used to refer to the process as applied to a variety of materials (e.g. plastics, glass, ceramics) whereas DMLS refers to the process as applied to metal alloys. The difference is that SLM achieves a full melt while DMLS sinters the powders, i.e., it heats them to the point that the powder can fuse together on a molecular level. This means that DMLS only works with alloys (nickel alloy, Ti64 etc.) while SLM can use single component metals such as aluminium or titanium. SLM can do the same as sintering and go further, by using the laser to achieve a full melt, achieving a homogenous part. With sintering, the porosity of the material can be controlled.

Due to the availability of an EOS M280 DMLS machine in the CAxMan consortium, this specific process will be investigated during the project. Nevertheless, the PP is almost identical both in the melting and sintering cases, where the main steps of PP are:

- Geometry repair;
- Part orientation within the building chamber;
- Design of support structures;
- Slicing of the geometry;
- Set of manufacturing parameters (e.g., scanning sequence speed, laser intensity, etc.) and toolpath generation.

2 LITERATURE ANALYSIS

An analysis of scientific literature was performed by CNR on the topic of Process Planning (PP) for Additive Manufacturing (AM) technologies. Several important studies were found.

The vast majority of the scientific publications ([1] [4] [7] [13] [15] [26] etc.) agree that the PP for AM technologies consists of at least five fundamental building blocks: geometry repairing, shape orientation, support structures, slicing and machine tool-path generation. Geometry repairing ensures that the design geometry unambiguously encloses a solid object. The shape orientation determines the way the shape is sliced and the material deposited - this choice is strategic for many reasons, spanning from building time to surface quality. Support structures deal with overhanging portions of the shape that need to be sustained from below so as not to collapse or cause a loss of balance of the object at printing time. Slicing consists in decomposing the shape into a set of planar parallel layers to be printed one on top of the other, whereas tool-path generation consists in generating the actual machine paths along which the printer will deposit material for each slice.

In the remainder of the section an overview of the state of the art PP tools and frameworks will be presented. A sub-section devoted to each fundamental building block will then complete the literature analysis presenting the most recent advances for mesh repairing, shape orientation, external support generation, slicing and tool-path generation. Finally, we will draw some conclusions that emerged from the analysis of the scientific literature in the field.

In [26] Gao and colleagues organize the body of knowledge surrounding AM and present current barriers, findings, and future trends significant to the research community. Fundamental attributes of AM processes, evolution of the AM industry, and the affordances enabled by the emergence of AM in a variety of areas such as geometry processing, material design, and education is also discussed.

In [1] Pande and Kumar propose a Computer Aided Process Planning (CAPP) for Fused Deposition Modelling (FDM). CAPP is meant to help the user finding an optimal model orientation according to different criteria (e.g. minimization of supporting structures, building time or quality). It supports both constant and adaptive slicing as well as different path planning techniques. Unfortunately, it is entirely focused on FDM and it inputs only 3D shapes that are represented by their external surface, making many of the technical solutions proposed in the paper unsuitable for Selective Laser Sintering (SLS) which, instead, requires an explicit volumetric representation of the model to be manufactured.

Verma and Rai [13] developed a generic and near real-time framework for unified AM PP, providing a quick and unified approach to quantify the manufacturing build time, accuracy, and cost in real time. Computational geometric solutions were developed to estimate tight upper bound of PP decisions that can be analysed in almost real time.

In Guoqing Jin PhD thesis [4] a set of novel, integrated and systematic adaptive process planning algorithms and strategies have been developed regarding the trade-off between geometric accuracy and build efficiency. The thesis focuses especially on adaptive tool-path generation and adaptive slicing algorithms for complex biomedical model fabrication and Functionally Graded Materials (FGM).

As many authors observed [7] [15] [26], the quality of the final product heavily depends on the parameters that govern each step in the PP pipeline. Zhang and Bernard [7] introduce a multi-attributes decision-making system (MADM) to select materials and determine a set of parameters to set up a process planning for AM. Furthermore, Chernow's thesis [15] develops a PP module to select an optimal set of parameters for AM.

Since in recent years the research to fabricate multi-material products by rapid prototyping (RP) is becoming very active, in [24] Li et al. propose an interesting update on the recent development of PP for multi-material RP. Notice that multi-material RP can be hard to implement in powder bed printers, because the printing chamber would need to be emptied and re-filled at each change of material, thus making the whole procedure extremely time consuming and error prone.

In [16] [18] [19] the authors discuss an interesting variation of the classical AM, where material can be deposited along two different directions (typically orthogonal to each other). In multi-orientation AM support structures are not needed and the surface is of higher quality. However, as for multi-material AM, this paradigm can be hard to implement in powder-bed printers.

The authors of [5] and [10] provide solutions to the orientation optimization problem of multi-part production, where a group of parts in the same build vat or chamber should be orientated simultaneously, with the goal of minimizing the total build time and cost at a global optimal level.

Luo et al. [12] propose a framework, called Chopper, to decompose a large 3D object into smaller parts so that each part fits into the printing volume. A number of desirable criteria for the partition is formulated and optimised, including assemblability, number of components, unobtrusiveness of the seams, and structural soundness.

In [38] the object is decomposed into approximate pyramidal shapes, such that each component can be described by a flat base plus a height field over the base. Shapes of this type are optimal for layered 3D printing because they do not require any support structure to be built. Notice, however, that pyramidal decomposition may affect the robustness of the shape once it has been re-composed, a crucial factor in many industrial applications.

Attene's papers [23] and [39] proposed methods to split a 3D model in parts that can be efficiently packed within a box, with the objective of reassembling them after delivery.

Heigel et al.'s work [25] focuses on the AM process simulation: a thermo-mechanical model of directed energy deposition AM of Ti–6Al–4V is developed using measurements of the surface convection generated by gasses flowing during the deposition. This phenomenon is studied to improve the finite element analyses (FEA) and ultimately simulate the effects of the large thermal gradients that generate plastic deformation and residual stresses.

In [11] and [40], Lu et al. propose two methods to reduce the material cost and weight of the part, while providing a durable printed model that is resistant to impact and external forces. The former proposes to fill the volume with a set of honeycomb cavities whereas the latter proposes a branching structure that emanates from the medial axis of the shape towards its outer surface. Note that none of these approaches can be implemented in a powder bed printer – in the case of the honeycomb structure it would be impossible to remove the remaining powder from the internal cavities, whereas for the medial axis tree the supporting structures needed to print it would be very hard to remove (the authors print them with a soluble material, which cannot be done in the context of metal printing).

2.1 GEOMETRY REPAIRING

Mesh repairing has received an increasing attention in recent years, not only for 3D printing, but in general for all the scenarios where a "well-behaving" mesh is required (e.g. finite element analysis, advanced shape editing, quad-based remeshing, etc.). Some repairing methods transform the input into an intermediate volumetric representation and construct a new mesh out of it [46]. These methods are very robust but necessarily introduce a distortion. Robustness and precision are indeed major issues in this area, in particular when self-intersections must be removed [44]. In this case some approaches rely on exact arithmetic, while some others can losslessly convert the input into a finite precision plane-based representation, and then reconstruct a provably good fixed mesh out of it [47]. When used for 3D printing applications, however, the aforementioned approaches are useful only if the input actually encloses a solid, while they are not really suitable to fix open meshes (note that some designers use zero-thickness sheets of triangles to represent thin parts). Furthermore, even if a solid is described, it might have features that are not compatible with the printing technology (e.g., too thin walls). For a more comprehensive overview of mesh repairing methods, we point the reader to [45].

2.2 ORIENTATION

Byun and Lee [14] studied the problem of determining the optimal build-up direction of a part for different RP systems. In their analysis they take into account a variety of elements, such as: surface roughness (e.g. stair stepping effect), build time (calculated by laser travel), part cost (calculated by build cost rate), labour cost rate, material cost, etc.

Thrimurthulu et al.'s work [20] is an attempt towards obtaining an optimum part deposition orientation for the FDM process for enhancing part surface finish and reducing build time. Models for the evaluation of average part surface roughness and build time are developed; then a real coded genetic algorithm is used to obtain the optimum solution.

Ezair et al. [21] explore the effect that the orientation of a printed object has on the volume of the needed support structure: the paper shows that the volume of the support is a continuous but non-smooth function, with respect to the orientation angles. It also presents an algorithm that computes the model support volume for a given orientation.

Alexander et al. [22] proposed to decouple the solution to the problems of determination of best build orientation and build cost minimisation from a specific LM (laser melting) technology, thus allowing the application of the solution to a variety of processes and providing more realistic cost comparisons of parts built on different machines.

2.3 EXTERNAL SUPPORTS

Dumas et al. [9] developed an automated support generation technique using little material while ensuring fine surface quality and stability during the printing process, by exploiting the ability of Fused Filament Fabrication (FFF) printers to print bridges across gaps overcoming drawbacks of current support generation systems. This system proved to be more reliable and robust than the tree-like supports generated by Autodesk MeshMixer [42].

In [41] an optimization framework for the reduction of support structures in the context of Fused Deposition Modelling is also presented. This method is capable of reducing the amount of material by a factor of 40.5% and the printing time by a factor of 29.4% w.r.t. previous approaches.

In [8] Schmidt and Ubetani propose a method to reduce wasted time and material in fused filament 3D printing by generating space-efficient branching support structures. In the example the support uses 75% less plastic than the manufacturer-provided supports, which also reduces print time by 25%.

2.4 SLICING

Volpato et al. [2] developed RP software to slice STL files, generate information for layer addition and send data to the machine. The main objectives are to obtain autonomy on the processing parameters and to develop a system which could be used in different RP technologies. The software was validated with the FDM process.

Zhiwen Zhao and Luc Laperrière [3] discuss the method of direct slicing, a technique capable of slicing a CAD model without passing through an explicit discretization of the geometry (e.g. converting it to a triangle mesh, typically coming in the form of an STL file). Direct slicing adapts the layer thickness to the shape so as to reduce the number of slices and aliasing artefacts (i.e. staircase effect), and it is a good alternative to crude geometric tessellated STL representations.

2.5 PATH PLANNING

Jin, Li and Gao [6] propose an adaptive approach to improve the PP of RP, basing on Non-Uniform Rational B-Spline (NURBS) curves to represent the boundary contours of the sliced layers, a tool-path generation algorithm to preserve geometrical accuracy, an adaptive speed of the RP nozzle/print head to address the geometrical characteristics of each layer and to identify the best slope degree of the zigzag tool-paths towards achieving the minimum build time.

Castelino et al. [27] developed an algorithm for minimizing the non-productive time or “airtime” for a tool by optimally connecting its tool paths. The problem is solved using a heuristic method.

King Wah et al. [28] studied the same problem and solved it by firstly introducing a Genetic Algorithm (GA)-based approach; then a new strategy is presented using a combination of the Asymmetric Traveling Salesman Problem and Integer Programming (TSP-IP) to solve it.

Volpato et al. [17] describe two methods for identifying the direction of each contour in a set, i.e., for sorting them into internal and external contours. Three alternative tests to check whether a point is inside or outside a polygon were evaluated. The tests are based on the ray-tracing principle and the classical point-in-polygon test. The proposed algorithms were devised and implemented in an AM process planning system.

2.6 FINAL REMARKS

From the study of the scientific literature the following points have emerged:

- Fundamental problems like mesh repair, shape orientation, slicing, tool path planning and external supports are common to all the printing technologies (though their solutions might change depending on the specific printer). The way these fundamental building blocks relate to each other is not completely understood and is to be considered as an open problem. Most authors agree that they cannot be treated separately - a better understanding of the mutual relations between the parameters that govern these steps would make 3D printing more predictable, less error prone and would ultimately produce higher quality objects;

- The solution to each fundamental problem is often both technology and material dependent. For example, good strategies for printing on plastic may not be as good (or even not apply at all) to powder bed printing, and vice versa;
- Technologies like Selective Laser Melting require an explicit volumetric description of the 3D objects to be printed. As many of the contributions in the literature deal with objects represented by their external surfaces, methods to convert a surface model into a volumetric one should be produced, and specific solutions may be found for each step of the PP pipeline (see also Section 3.3.2 in Deliverable D2.1);
- The problem of balancing between weight and structural strength is somehow controversial. Printing a dense model would make it very strong but would require too much material and would dramatically increase its weight (see Section 5 in Deliverable D2.1). Depositing only a thin layer of material on the outer surface would make the model lighter but also structurally fragile. Methods that try to find the trade-off between weight and strength propose inner structures that, to be printed, would require external supports which are difficult to remove after printing. Moreover, they do not consider that the final shape may be completely closed, and its interior inaccessible after printing. Last but not least, for powder based technologies a way to remove the residual powder after printing needs to be taken into account at the early stages of the pipeline.

Summarizing, here is a list of the main factors to take into account for a PP pipeline:

- Mesh repairing: does the design geometry unambiguously enclose a solid object? Is such a solid "printable" with the technology at hand?
- Volume decomposition: does the shape fit the printer volume? Is the shape subject to structural constraints (strength, resiliency to external forces, etc.)? Will the part be decomposed for packing/shipping? Will it be decomposed to avoid external supports?
- Shape/part orientation: what are we optimizing for (cost, speed (minimize height along slicing direction), surface roughness (avoid the staircase effect), minimize external supports, model strength (w.r.t. to e.g. external forces), mixed factors)?
- Shape editing: do we need external supports? Will the shape be corrupted during printing (e.g. thermal analysis)? Do we need to edit the surface to make the object more robust? Do we need to fill the interior to make it stronger (e.g. cavities)? Are there closed chambers impossible to empty after printing?
- Slicing: regular/adaptive?
- Toolpath: how do we print each slice?

3 CURRENT PP FOR AM TECHNOLOGIES

Tronrud is a user of AM technologies. In particular, the company uses an EOS 280 machine for DMLS on a daily basis. The partner was therefore asked to describe the current PP used to manufacture parts with the EOS 280 machine. According to Tronrud's experience, two main PPs can be distinguished:

1) Input is a STEP/CAD model: in the majority of cases, the process starts with the native CAD file. In this case, the part may be modified to add machining allowance (in case of surfaces that must be finished by subtractive methods) and the part orientation is decided at the very beginning, just before the tessellation that converts the CAD geometry to an STL file.

2) Input is already in STL format (in some cases Tronrud directly receives an STL and has no access to the original CAD geometry): here any modification to the part geometry is much harder and the PP does not include the design of machining allowances.

The key steps of the baseline PP are described in Table 1.

TABLE 1: BASELINE PP FOR AM.

Task	Description	SW used	Issues/challenges
Import to CAD (Figure 3)	Formats supported: Step, iges, parasolid, Native NX	Siemens NX	Faults in the imported geometry (holes, overlaps, bad surface blends, etc.).
Add machining allowance	Subtractive methods must be used on surfaces requiring a high quality finish. If the designer of the part has not taken this into account, the allowance must be added at this stage.	Siemens NX «Synchronous Modeling» application	For complex geometries it may be difficult to add allowance with the same shape as the part – results in adding more material than actually necessary (simple geometric shapes) that has to be removed in the subtractive processes.
Plan the part orientation	Based on experience from both AM and conventional subtractive manufacturing, the operator decides how the part should be oriented in the building chamber to minimize need for support structures and avoiding stress build-up during the printing process.	Siemens NX	The «qualified guess» of the operator may not be successful, so the part may deflect or faults may occur that results in a product outside of the desired tolerances. This typically leads to a «trial and error» approach where several attempts are needed to achieve the desired result.
Convert to STL file	Conversion of the CAD file to the standard file format used for the printing preparations.	Siemens NX	Resulting STL file may have faults; bad triangles and/or overlapping triangles (the list of problems is reported in a file by the CAD software, NX in Tronrud's case); the operator is then aware of problem areas. In extreme cases the design has to be changed and the steps above repeated on the new geometry.

(starting point an STL file)	If an STL file is the «starting point», none of the above tasks can be performed.		Any machining allowances must have been added by the designer.
Geometry repair	Opens the STL file in «Materialise Magics». The software repairs the geometry automatically.	Magics	Often more faults are found here than in the previous operation (STL export). If some faults remain after the automatic repair, the fix may be done manually, but the software is not very good/user friendly for this purpose. The printing process may be attempted if there are not too many faults – but the results are unpredictable and the process may stop «anywhere». The geometry repair is the most critical part of the preparations – it has the biggest impact on the result.
Orient the part	The model is oriented relative to the building platform based on the evaluation/planning done in the CAD system. Typically a distance is set between the platform and the bottom of the part, and an angle is set between the platform and a convenient surface of the part.	Magics	Usually no problems.
Adding support structures (Figure 4)	The link between the printed part and the baseplate of the 3D-printer is a «support structure» (lattice) that is sawn or broken off when the part is finished. The support structure also transfers heat away from the part (into the platform). Surfaces with an inclination of less than 45° relative to the building platform need a support structure. (Each layer has to build on top of a previous one.)	Magics	The density of the lattice structure is determined by the operator. If high internal stresses in the printed part are expected the density needs to be relatively high to be able to keep the part firmly in position. This may also lead to a «trial and error» approach – several prototypes may be required to reach the desired quality of the finished part. The variable density of the lattice structure also enables the operator to determine the spacing of the contact points towards the part. A normal support structure builds square pillars from the platform up towards the part surface and close to the part the square shape may be converted to a number of «points» that the actual part surface is built

			upon. The density of the lattice and the spacing of the contact points determine how well the support structure is attached to the finished part. If the attachment is insufficient (low density support) the part may be deformed or even loosen from the platform. If the attachment is close to «solid» it may be impossible to remove the part from the support structure without some form of machining operation.
Slicing	Slice the geometry into layers. Output is an SLI file that is used in the 3D-printer. The operator determines the layer thickness, typically 0.03-0.06 mm (depending on the type of material and desired quality of the finished part).	Magics	Usually no problems, software slices automatically. Layers may be «played» one by one on screen for a visual control of the printability. Each layer must build on the previous one; if geometry starts to appear outside of the part that is built to the current layer, it will not work.
3D printing	Open the SLI file in the EOS machine software (Figure 5). Specific location of the model on the building platform is set. Possibly fill the available print area with models to be built. Push Play.	PSW	Typical problems during printing: -Deformation of the part, may lead to collision between part and powder applicator. -«Meltdown» – local heat build-up that melts the surrounding area, building surface of the part collapses, and it is not possible to continue printing. -Printer stops due to many errors in the source-file (STL).

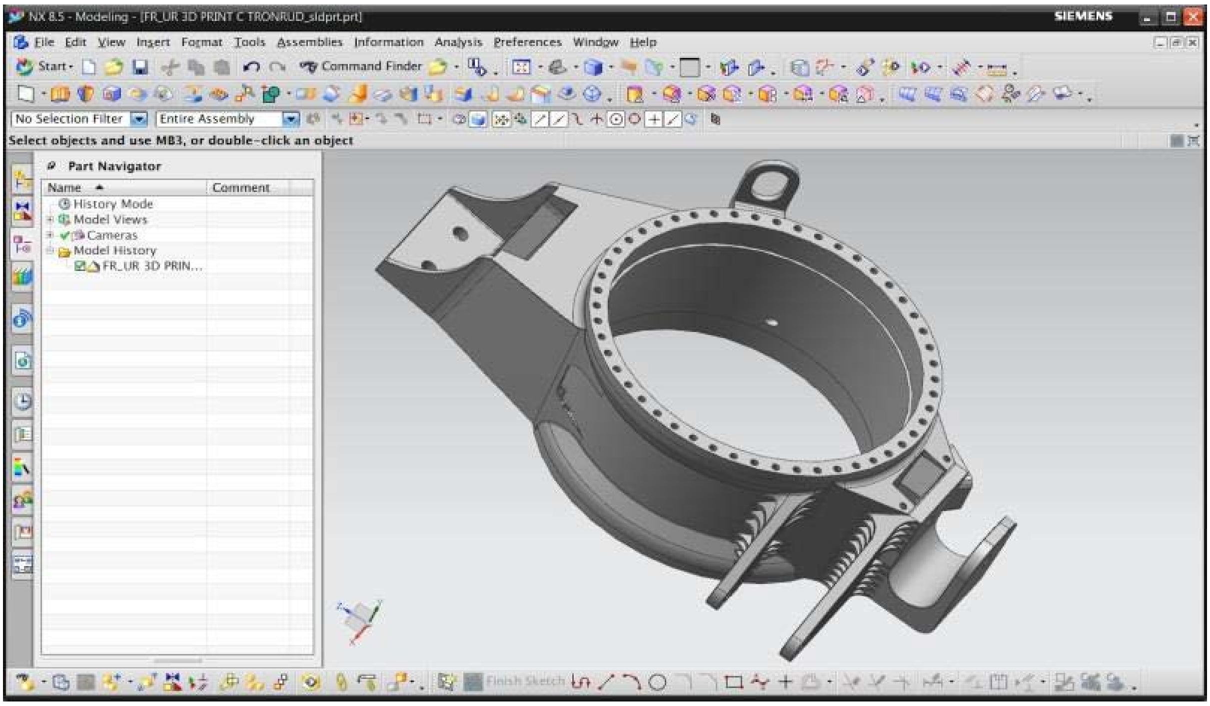

FIGURE 3: EXAMPLES OF A STEP-FILE IMPORTED INTO CAD-SYSTEM.

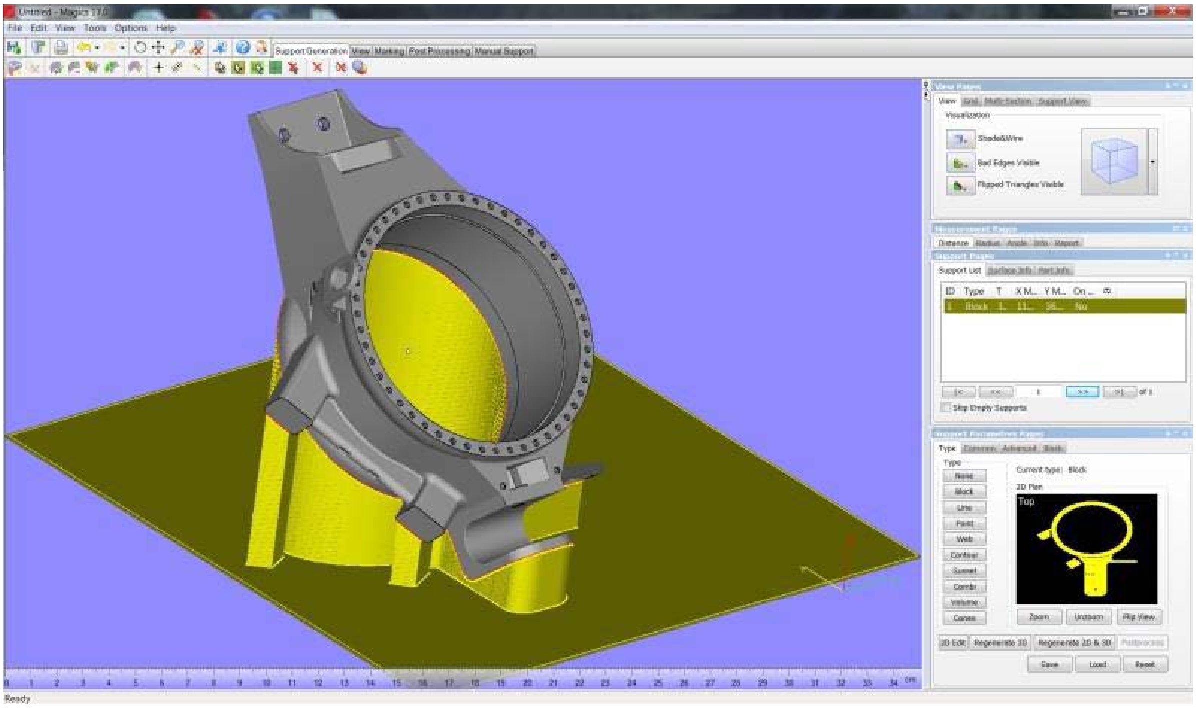

FIGURE 4: STL-FILE OPENED IN MAGICS, ADDED SUPPORT STRUCTURE (YELLOW).

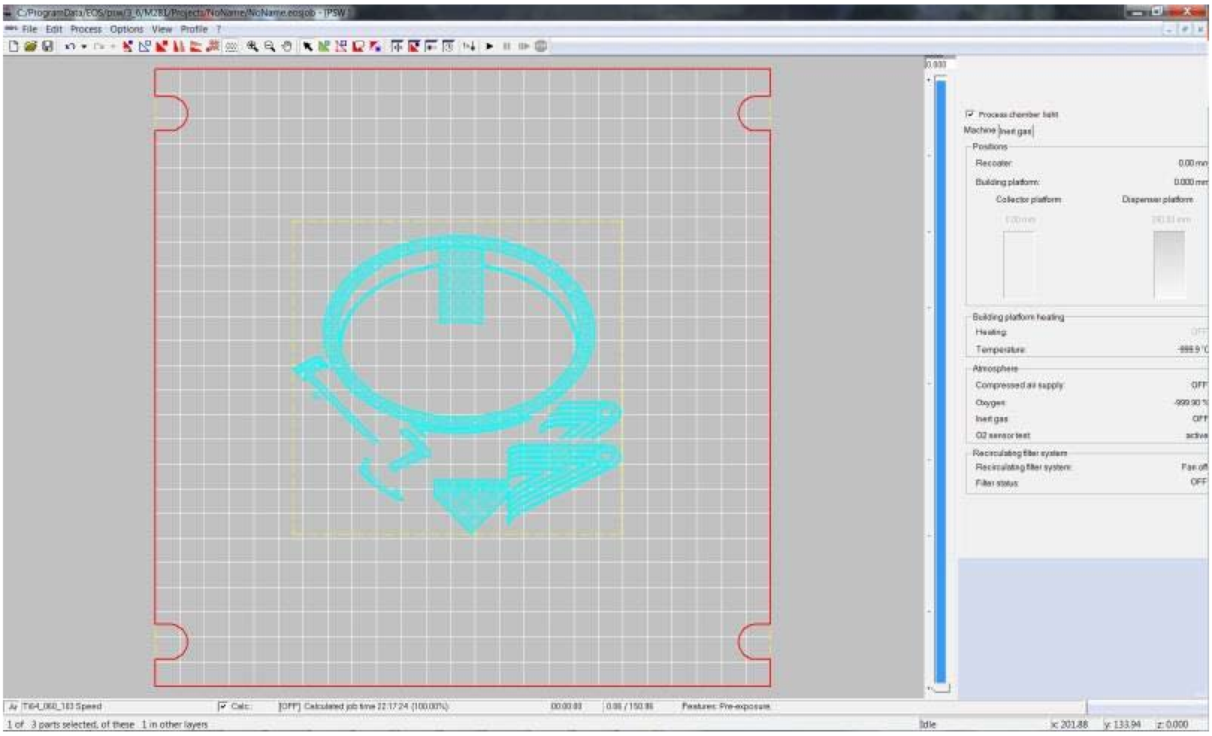

FIGURE 5: SLI-FILE OPENED IN PSW (EOS SOFTWARE), PLAYING LAYERS.

As described in Table 1, currently Tronrud's PP does not include the generation of a toolpath. In fact, Tronrud's printer automatically computes the toolpath internally, and the toolpath cannot be accessed or modified.

According to the relevant experience of Tronrud as user of AM technologies, the key issues of PP are:

- The STL geometry repair;
- The design of support structures;
- Local meltdown of the part that cause process failure.

4 REQUIREMENTS OF PLASTIC 3D PRINTING

This section outlines the PP tasks that are usually necessary to print on plastic using low-end fused deposition printers, such as the widely diffused Makerbot products.

In this case we assume that the input is already in triangulated form. As shown in Table 2, tasks and issues to reach this stage are essentially the same as those already outlined by Tronrud.

TABLE 2: CONSUMER LEVEL 3D PRINTING PP TASKS AND ISSUES.

Task	Description	Issues/Challenges
Original format to STL file	A triangulated 3D model must be converted to STL format (if not already in that format)	Widely diffused formats such as .obj .ply or .off use an indexed representation to encode triangulated surfaces – a conversion to the STL file format must be performed, replicating vertex coordinates for each and every triangle, thus generating an STL file approximately six times bigger than the original one.
Mesh repair	Faulty geometry must be fixed so that the mesh unambiguously encloses a solid.	Faults such as holes/missing parts (e.g. the model is not watertight), bad triangles and/or overlapping triangles, and self-intersections must be fixed. Completely automatic repair is not always possible. If some faults remain after an automatic repair, the fix may be done manually, but the process can be tedious. If this is the case, the printing process may still be performed but the results are unpredictable and the process may stop at any point.
Shape repair	The solid enclosed by the mesh must be made printable with the technology at hand.	The solid might include thin walls whose thickness goes below the printer resolution; printing models with cavities with powder bed printers is not an easy task (powder remains trapped within the cavities); the model size exceeds the printing volume (see orientation and decomposition tasks). Solutions are necessary here.
Model decomposition	Should the model be too big, it is decomposed into sub-parts so as to fit the printable volume of the machine.	Decomposed models may be structurally weaker. Prior knowledge on external forces/stresses the printed objects will undergo may be encoded in the decomposition process. Proper junctions should be inserted at splitting boundaries so as to ensure maximal adherence between parts.
Part orientation	Parts are oriented relative to the building platform to minimize the need for support structures, maximize stability during the printing process (e.g. avoid loss of	A good orientation may be difficult to find. This typically leads to a «trial and error» approach where several attempts are needed to achieve a satisfactory result. A more automated approach that

	balance), minimize printing time (e.g. number of layers to print) and maximize surface quality (e.g. avoid staircase effect, warping).	takes into account the underlying variables would be useful. - warping: the printed object detaches from the building plate, resulting in a squeezing of the first layers. This typically occurs when printing an object that has a large footprint; it may be avoided by inserting a raft in between the building plate and the first object's layer so as to ensure maximum adhesion, but this is not always sufficient. Orientation cannot always solve this issue.
Support structures	Surfaces with an inclination of more than 68° from the building direction usually require support structure (each layer has to build on top of a previous one). Supports are removed once the part is finished.	Both the amount and density of support structure is determined by the operator. Factors to consider are: the angle at which supports begin, the support pattern, its density and the space between model and support. This may lead to a «trial and error» approach – several prototypes may be required to reach the desired quality of the finished part. Typical problems that may arise are: - dropping plastic: unsupported material will drop because of gravity. This can be fixed with additional supporting structures; - supporting structures that are hard to remove, because of their proximity to the surface or inside tunnels/cavities; - waste of material; - low quality of the surface after removal of support structures.
Slicing	Slice the geometry in layers. Layer thickness can be uniform or it may vary according to the morphology of the object. Thicker layers usually lead to faster printing at the cost of lower quality.	Fixed thickness slicers work out of the box but may result in poor quality. Adaptive slicing is a good alternative, but it is not easy to determine the best strategy to optimize for slice thickness. There are several criteria, such as precision and volumetric error, but also aesthetics of the final part.
Toolpath	Generate the 2D paths the printer needs to follow to build the object. These are usually in the form of a G-Code (NIST RS274NGC G-code standard). In consumer-level plastic printing shapes are usually described by their outer surface only. Filling the whole volume with plastic would be a waste of material, thus to give the printed models more strength the internal area is filled with a	- The type of filling determines the structural strength of the object. It should adapt to the various features of the shape to maximize strength while minimizing material usage, but current techniques just use a constant pattern everywhere. - warping: the printed object may detach from the building plate, resulting in a squeezing of the first layers. This typically occurs when printing an object that has a large footprint; it may be

	sparse honeycomb structure, whereas a full filling is used nearby the outer surface.	avoided inserting a raft in between the building plate and the first object's layer so as to ensure maximum adhesion. Warping may occur at higher layers too, and in this case no satisfactory solution exists yet.
3D printing	The G-Code is converted to a machine-specific language (e.g. S3G, X3G) and sent to the printer (e.g. through USB or by using an SD-card). The location of the model is already encoded in the G-Code and cannot be changed at this stage. Push Play.	Typical problems during printing: low adhesion to the building plate, warping, etc.

5 PP REQUIREMENTS ACCORDING TO THE PRODUCT DEVELOPMENT ACTORS

The requirements of PP are different according to the various actors of the product development flow. At the beginning of project activities STAM collected the requirements of the following key stakeholders in the CAxMan consortium:

- STAM and NOVATRA provided the requirements according to the end-user perspective;
- SINTEF provided the requirements of the design and simulation phase;
- Tronrud provided the requirements of an AM user.

The questionnaires distributed to the partners were customised depending on the role of each stakeholder.

5.1 END-USER PERSPECTIVE

Both use case providers (STAM and NOVATRA) were asked the same questions, to collect the PP requirements from the perspective of the mechanical parts designer/developer.

1. ***Please rank by 1 to 10 the following features which characterize an optimal Process Planning for manufacturing your part (1 = not pertinent, 10 = fundamental feature):***

    - Reduction of geometric issues in the STL file. STAM: 7; NOVATRA: 6.
    - Reduction of defected parts (thermal distortions minimized by means of optimal orientation and support structure). STAM: 9; NOVATRA: 8.
    - Reduction of processing time (by means of optimal orientation and support structure optimization). STAM: 10; NOVATRA: 8.
    - Reduction of areas to be finished by subtractive methods. STAM: 8; NOVATRA: 8.
    - Increased predictability of the AM process even in case of faults in the STL file. STAM: 6; NOVATRA: 6.

2. ***Please rank by 1 to 10 the following parameters which characterize an optimal final result (1 = not pertinent, 10 = fundamental parameter):***

    - Reduction of development/engineering time (though increased software interoperability). STAM: 10; NOVATRA: 8.
    - Reduction of manufacturing time. STAM: 8; NOVATRA: 8.
    - Reduction of parts weight. STAM: 9; NOVATRA: 5.
    - Reduction of surface roughness. STAM: 7; NOVATRA: 6.
    - Reduction of parts cost, through:
        - Manufacturing time reduction? STAM: 8; NOVATRA: 8.
        - Manufacturing steps reduction? STAM: 8; NOVATRA: 8.

- No tooling needed? STAM: 9; NOVATRA: 8.

3. In your opinion, what characterizes an optimal PP?

STAM: All the features of the first question are important: reduction of defected parts and production time are especially relevant.

NOVATRA: An increased accuracy of the AM technology.

4. Which additional Key Performance Indicators should we consider to quantify the improvements in the PP?

STAM: As far as the NUGEAR use case is concerned, the weight of the parts, their cost and the efficiency of the gears (strictly connected to the surface finish in the teeth) are the most important KPIs.

NOVATRA: The reduction of cost of the AM technology.

NOVATRA also specified the company's expectations from the AM usage and from the CAxMan project in general (see Figure 6 and Figure 7).

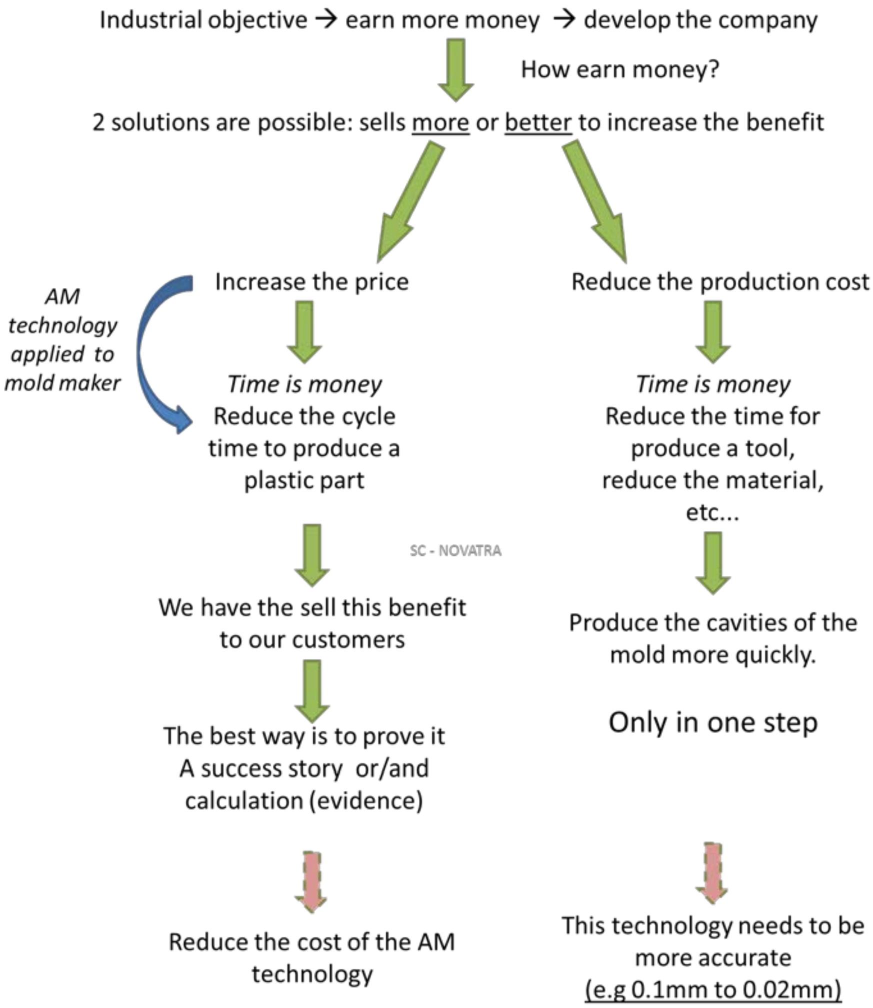

FIGURE 6: NOVATRA'S EXPECTATIONS FROM AM.

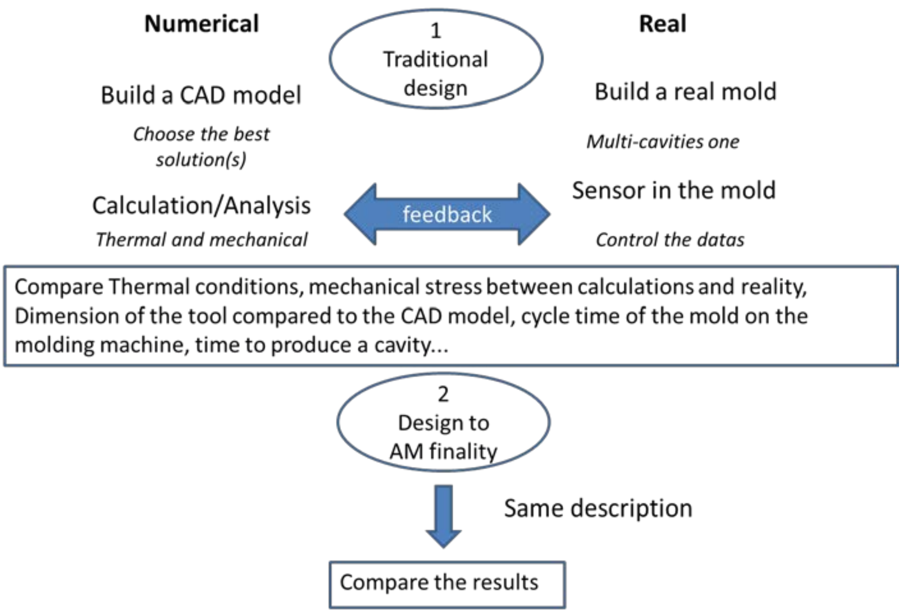

FIGURE 7: VISION OF THE WORKFLOW

5.2 DESIGN-SIMULATION EXPERT PERSPECTIVE

A questionnaire was sent to SINTEF, in order to gather the requirements of PP from the perspective of an expert in part design (mathematics) and simulation.

1. ***With reference to the CAxMan use cases (NUGEAR and Injection mould), how do you think the Process Planning could contribute to obtain the maximum quality result for these parts?***

   Orientation of the models in the build volume with respect to the resulting manufactured shape is an important consideration. For some geometries there are large differences between manufacturing horizontally and manufacturing vertically, which can result in distortions (e.g. printing a cylinder vertically gives different results to printing a cylinder horizontally). Good process planning should take into account orientation to maximize quality of the part.

   Post additive machining should be considered for parts that need to be smoothed, for example, this is probably important at least for the contact parts of the NUGEAR.

   Manufacturing complex voids such as cooling channels in the Injection Mould with high quality is challenging. The process plan must take into account the need to remove powder from the cooling channels after the AM process. It could also check the integrity of the geometry to ensure certain characteristics (e.g. minimum wall thickness).

   Poor quality powders appear to be another issue. Optimizing the position/orientation of the models to be printed in a single build volume will reduce the amount of powder needing to be reused, thus better maintaining the quality of the powder.

2. ***With reference to the CAxMan use cases (NUGEAR and Injection mould), how do you think the Process Planning could contribute to keep at minimum the manufacturing time for these parts?***

Taking into consideration the chosen manufacturing methods, the orientation of the models in the build volume will probably be the most important consideration for reducing time (applies to both use cases). For certain orientations fewer layers are required and thus less powder will need to be deposited. For example, if the model has one dimension that is much larger than the others (the diameter), that direction should not be manufactured vertically. The choice of orientation, of course, has to be balanced against any structural/physical quality requirements (e.g. need for extra support structures, distortions, etc.). We also expect that by introducing voids (as will be done in WP2) the process will be quicker since less time is required for laser sintering on each layer.

3. ***With reference to the CAxMan use cases (NUGEAR and Injection mould), how do you think the Process Planning could contribute to keep at minimum the waste material for these parts?***

Additive manufacturing is inherently less wasteful than many subtractive processes, since the powder that is not sintered can be reused in subsequent AM processes. However, it must be kept into account that the quality will deteriorate with repeated reuse and the powder grain size change through reuse will affect the quality of the final product as well.

The main waste is probably from any support structures that need to be removed post AM. Process planning can contribute to minimizing the need for support structures. Careful process planning is also needed to reduce defective products that need to be scrapped (e.g. by checking that the model geometry can be manufactured by the given process).

As mentioned, reducing the amount of powder that needs to be reused can contribute to reducing waste, so orienting and positioning the models is important to maximize the utilization of the build volume.

4. ***With reference to the CAxMan use cases (NUGEAR and Injection mould), how do you think the Process Planning could contribute to optimize and minimize the support structures for these parts?***

Powder bed methods are self-supporting to a certain extent, but the process planning stage needs a good understanding of the process to know when/where support structures are needed. For printing single objects an obvious optimization is to keep the largest dimension in the xy-plane, so that the weight is distributed over the powder bed, but as mentioned earlier this can give bad results (c.f. cylinder example). Thus, it may be better to orient the objects vertically, especially if you know that several can be manufactured simultaneously.

5. ***In your opinion, what characterizes an optimal PP (e.g. reduction of development/engineering time through increased software interoperability, reduction of manufacturing time, reduction of parts weight, reduction of parts cost, etc.)?***

The process plan should be streamlined in the infrastructure, so that for a given geometry the process plan will be generated efficiently. This will probably involve a lot of automation, but also some user interaction. The plan should aim to optimize with respect to all the parameters (reduction of development/engineering time, reduction of manufacturing time, reduction of parts weight, reduction of parts cost, etc.), whilst maintaining the quality of the components. Some parameters such as “reduction of weight” are probably more relevant to WP2 though.

6. ***In your opinion, which Key Performance Indicators should we consider to quantify the improvements in the PP?***

- Reduced material usage
- Cost efficiency
- Reduced development/engineering time

5.3 AM USER PERSPECTIVE

Finally, another questionnaire was sent to Tronrud, in order to collect the requirements of PP from the perspective of an AM technology user and part manufacturer. Some of the questions refer to the baseline PP summarised in Table 1.

1. ***Plan the part orientation: specifically, which kind of problems (part defection and faults) can arise because of a non-optimal orientation?***

   If the part is oriented in a bad way, it is hard to obtain the tolerances, due to the “meltdown” in holes and “roof” structures. Horizontal holes (centreline parallel to the building platform) and cavities with a closed “roof/ceiling” will have an increased wall thickness towards the top; the top section will “sag” a little bit due to excessive melting/heat build-up (the heat melts powder that is below the actual part).

   It may also be impossible to print due to the build-up of tension in the parts (the part deflects/twists out of shape). This can be compared to welding on only one side of a pipe or bar; it will bend/deform because the heated bar will shrink when it is cooling down.

   Another problem is that the chosen orientation may result in adding more support than actually needed (compared to the level of support necessary in an optimally oriented part). Bad orientation may also require that support structure is added in places where it is difficult, or even impossible, to remove.

2. ***Geometry repair: this step of the process seems crucial, why does the machine stop because of the STL file? How can we avoid this?***

   The STL file is the source for the SW that is used to slice the part and generate the SLI file.

   Overlapping triangles and bad triangles that are not repaired by the SW (in our case Magics) will result in an SLI file containing faults (not very good error messages from the SW, and limited possibilities for manual repair). We believe that faults are normally discontinuities in the geometry. As described in Table 1, the behaviour of the machine is unpredictable when it is using SLI files with faults; sometimes it works, and sometimes it does not.

3. ***Adding support structures: in order to establish the need for a support structure, does the software take into account only the slope angle, or also other aspects (e.g. center of gravity of the part and consequent part stability as a function of its weight)?***

   The program only makes support where the slope angle is below 45 degrees, it does not take other factors into account. Our general understanding/opinion is that the support suggested by the SW is discarded in 95% of the cases. It is done manually to have better control.

   The operator chooses manually each surface he wants to have support on, and the SW generates support on that specific surface. This takes time, and the operator needs a good understanding on how the parts behave in the printer, and how much support is needed to hold the part in place.

4. ***3D printing: what causes the deformations of the part?***

- Tension in the building process (heat causes shrinkage and resulting tension).
- Insufficient support or support in wrong places (not able to keep the part stable).
- Meltdown on roof structures (inside surface "sag" and wall thickness increase).

5. ***Is it possible to manufacture multi-material parts with your printing machine?***

Yes, it is possible, but not really an option. The printing process may be stopped after any layer (chosen by operator), then all the powder must be removed from the machine, and another material must be loaded before the printing process can continue.

In metal printing this is difficult, due to the bonding of the two different materials with their unique physical properties (e.g. different heat expansion).

Combining two materials in metal additive manufacturing is not normal to do yet. More rough methods like welding of different materials (e.g. hard chrome onto steel). In plastic printers and cheap extrusion printers it is normal with more than one print head, and then it is possible to make multi material parts. As for metals, there is a problem with different melting temperature of the materials, so the bonding is very often a problem.

6. ***If the machine cannot manufacture multi-material parts, do you have any experience on this kind of AM technique?***

Didrik Sørlie (DMLS Engineer at Tronrud) has some experience having run tests with the materials we have in stock, but as described above this is not really a desired process for our machine.

We do not have a lot of experience when it comes to plastic, but as far as we know all the expensive and high quality AM-machines usually only run one material at the time. This probably has to do with the quality control and guarantee for an optimal product (usually given by the AM-machine supplier, provided their specified parameters are used).

7. ***In your opinion, what characterizes an optimal PP?***

For a manufacturing situation it would be nice if the PP does not require much operator time and results in as little manual work as possible (e.g. geometry repair).

It would also be good if the PP suggests changes if there are geometric problem areas that should be fixed in the design stage. At least it should locate the problem area and give a good error message so the designer can improve the geometry.

8. ***Which additional Key Performance Indicators should we consider to quantify the improvements in the PP?***

- Time spent on the PP process (by the operator)
- Number of faults automatically repaired
- How much of the automatically created/suggested support structure is useable/of good quality (we find that in most cases 95% has to be discarded on complex geometries).

9. General comments on AM-technology:

- Our understanding of the metal printing part of the AM-market is that all the suppliers are focussing on simplifying the operator's job (reducing or simplifying the steps from CAD to print). Also, a lot of the machines are using the same software (Magics), but with different add-ons/post-processors (e.g. EOS and SLM).

- There are big differences between the various AM-technologies both in terms of material used and the operating principle of the "printer" (plastic, metal, powder bed, extrusion, metal wire, welding, etc.). We find it hard to believe that one single PP will cover all these.

10. Input to the steps in front of PP:

The "mind-set" of the designer should fit the AM-process from the start (and today, perhaps also the machine to be used), i.e. not think like you would do if you should make the part by machining. Our experience is that if the manufacturing process is not considered during the design, the parts always get extremely expensive and in most cases too heavy.

Unnecessary material needs to be removed, and the designer also needs to think about how the part should be oriented when printing. They also need to think about how to get the powder out from the inside of the part after printing (all powder must be removed before heat treatment).

5.4 CONCLUSIONS OF THE STAKEHOLDERS PERSPECTIVES

Following the analysis of stakeholders' requirements, the following conclusions can be drawn:

- The key requirements for the use case providers are the reduction of defected parts and of processing time: this means that it is of utmost importance to solve the PP issues that may cause defects on the part, to reduce the PP duration and to optimise the AM process in order to save production time.

- More generally, PP should be aimed at reducing: development/engineering time, manufacturing time, parts weight, parts cost and improve surface finish.

- In this regard, the generation of supporting structures can be optimised with respect to: production time, part cost or part quality. In particular, a weighted average of these parameters can be optimised, or one of the indicators can be optimised keeping the other two as a constraint of the problem.

- Orientation of the models in the build volume with respect to the resulting manufactured shape is an important consideration, affecting part quality and cost. So this, together with the supports design, will be deeply investigated.

- The PP should aim to optimize with respect to all the parameters (reduction of development/engineering time, reduction of manufacturing time, reduction of parts weight, reduction of parts cost, etc.), whilst maintaining the quality of the components. This will probably involve a lot of automation, but also some user interaction.

- The automatic generation of supports is nowadays unreliable and a good PP must build on the experience of the operator. A strong effort should be devoted to address this issue by taking into account all the aspects related to the supporting structure (e.g. stability of the part because of the weight increase during manufacture and of thermal phenomena).

- The main KPI identified are:
    - Reduction of material usage (part weight and supporting structure needed) keeping the quality/function of the part unchanged
    - Reduction of defected parts (regardless the issue that caused the discard)
    - Reduction of PP time (through a smarter automatic generation of supporting structures and more effective geometry repairing routines)
    - Reduction of manufacturing time
    - Reduction of part cost keeping the quality unchanged (regardless the way to reduce cost)
    - Number of faults automatically repaired
    - Percentage of useable support structure automatically created/suggested

6 THE "OPEN PARAMETERS" ISSUE

As stated above, Tronrud's printer automatically computes the toolpath internally, and it is closed source (we cannot access such a toolpath). This may be caused by the fact that the user in most cases is concerned with the quality of the finished product and easy running of the machine. The supplier of the machine is also aiming for its customers to be productive and competitive and therefore has built in some features to prevent the user from adjusting parameters that may result in poor quality parts.

However, the EOS machine manufacturer provides the "Part Property Management" software, which allows modifying the parameters that influence the properties of the finished product. Two levels of customisation are allowed: a predefined "ParameterSets" (Speed, Performance and Surface), where the machine guarantees a certain quality, and the real "Parameter Editor" where the user can experiment. However, some critical parameters are still protected even within the "Parameter Editor": the start values include factory default values for the respective materials and layer thicknesses, ensuring that a standard build is optimally achieved.

6.1 THE "PARAMETERSETS" OPTION

ParameterSets offers standardization across all metal systems by ensuring defined Part Property Profiles (PPPs). These provide reliable values for the dimensioning of laser sintering designs. Among these are values for tensile strength, elongation at break, and moduli of elasticity for the horizontal X/Y direction, values for the vertical, orthogonal Z direction. A variant of this option is the "Custom ParameterSets": EOS develops a parameter set specific to the customer's application and part quality needs with protected or editable parameter values as well as a licensing model. This ensures consistency of the part quality regardless of the manufacturer, e.g. third party suppliers. Invisible parameter values protect the customer's IP. The licensing model gives the customer the ability to control usage and payment.

The PPPs typically include the following groups of properties:

- Geometric properties such as minimum wall thickness and surface roughness
- Mechanical properties such as tensile strength, yield strength, elongation at break, modulus of elasticity and hardness, and where applicable dynamic fatigue life
- Thermal attributes such as thermal conductivity, specific heat capacity and thermal expansion coefficient
- Properties affecting cost such as build-up rates (mm^3/s) [29]

6.2 THE "PAREMETEREDITOR" OPTION

On the other hand, the "ParameterEditor" option provides much greater flexibility. The package includes licenses for:

- Baseline: parameter values for available layer thickness for respective material
- ExposureEditor: editing functionality
- Material: machine settings and controls (ParameterSet)

This option allows:

- Selecting from multiple exposure types for preexposure, skin, core, contour and supports
- Editing multiple parameters per exposure type such as laser power, scan speed, hatch
- Assigning to entire job and/or each part

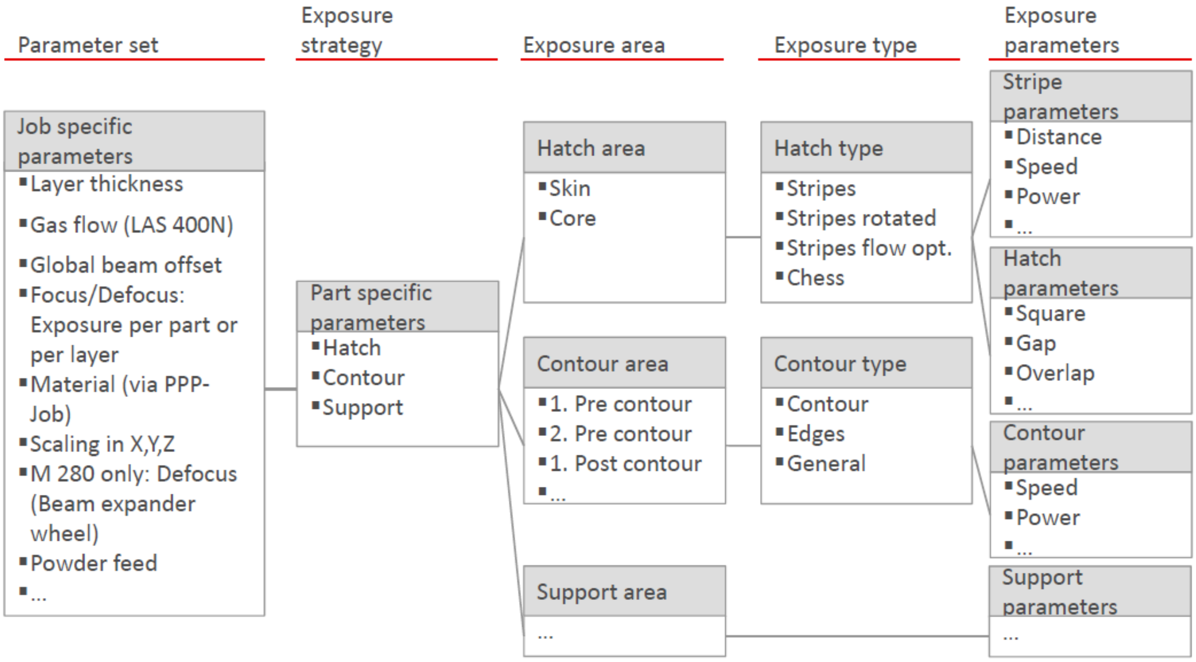

FIGURE 8: MAIN PARAMETER VARIATIONS.

The global modifications allowed are:

- Global beam offset
- Focus/Defocus: Exposure per part or per layer
- Material (via PPP-Job)
- Gas flow (LAS 400N)
- Scaling in X,Y,Z
- Defocus (Beam expander wheel)
- Powder feed

Besides, for the areas of the part and the support (see Figure 9), the following parameters can be varied:

- Contour parameters
    - Number of contours
    - Laser power
    - Scanner speed
    - Beam offset
    - Pre-/ Postcontour
- Hatch
    - Laser power
    - Scanner speed
    - Line distance
    - Beam offset
    - Hatching strategy
    - Stripe width
    - Skywriting
- Thickness of skin and core [30]

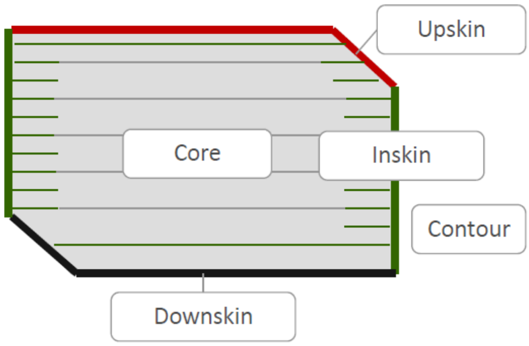

FIGURE 9: AREAS OF THE PART WHERE THE PARAMETERS CAN BE EDITED

Surprisingly, in the PSW version sold with the M280, the Developer Kit does not allow to override the default layer thickness. This can be done with successive versions of the PSW which, however, are not backward-compatible with the M280.

As far as the process monitoring is concerned, the following machine/process conditions are monitored:

- Laser status
- Scanner status (automatic self-calibration, 'Home In')
- Cooling system status
- Build platform position measurement via glass scale
- Build platform temperature
- Process chamber oxygen-level
- Process chamber temperature
- Process chamber humidity [31]

6.3 REMARKS ON THE "PARAMETEREDITOR" OPTION

In a recent PhD thesis by Kai Zeng [35], Section 4.1, the following statement appears: "Shrinkage and thermal stress-induced deformations are two key sources of defects in SLM which can be alleviated by better design of scan patterns. To accurately predict process outcomes, it is critical to simulate the SLM process using the exact same scan pattern as those used during the fabrication process". This same requirement has come from the providers of the simulation tools within CAxMan's consortium (i.e. CIMNE).

While using an EOS M280 printer, users cannot control the parameters that define the scan pattern unless they have the "Parameter Editor" module installed. It is not even clear whether these parameters can be accessed in read-only mode. According to Triantaphyllou and colleagues [43], given a material and a layer thickness, "There is only one available parameter set and the parameters are locked and not visible to the operator".

7 PP IN CAXMAN

In CAxMan we will have to implement PP workflows that involve a communication with both the design phase (WP2) and the thermal simulation (WP4).

In particular, the thermal simulation done in WP4 is strictly based on details of the printing process used (e.g. the scanning sequence). In the project, the demonstrator will use an EOS M280 DMLS machine provided by Tronrud. The software that drives this machine (EOS PSW) uses some default parameters that define the printing process (EOS Defaults). Hence, we have three possibilities here:

1. The default parameters cannot be accessed in any way, not even in read-only mode. In this case it would be extremely difficult to implement WP4 findings, because we are not able to use them as an input.
2. The default parameters can be accessed in read-only mode. If so, WP4 can perform the simulation, but if the thermal analysis suggests that the default scanning sequence would produce a bad result, we cannot change the parameters to test alternatives. In other words, we cannot perform actual experiments and provide a demonstrator for our WP3-WP4 feedback loop.
3. The default parameters can be changed. This is what we need to actually implement the framework.

To summarize, it is strongly suggested that the CAxMan Consortium invests in the “ParameterEditor” option of EOS, to fully interact with the machine. In fact, not only will this option make the parameters available in “read mode”, but it will also allow to change some of these parameters in order to optimise the AM process.

7.1 OVERVIEW OF THE PROCESS PLANNING TASKS

In CAxMan the PP involves at least three sequential steps:

1. Model preparation (mesh/shape repair, orientation, creation of support structures, etc.)
2. Slicing
3. Scanning sequence calculation

The issues related to the STL file can be of two types:

- Mathematical issues, such as: reversed normals, bad edges, holes in the mesh, noise shells, intersecting triangles, etc. These should be effectively and autonomously solved by mesh repairing routines. Even though the routines may provide a sufficiently accurate result, a design verification (WP2) of the proposed solution may be requested.
- Physical issues: very thin surfaces (that may warp or collapse), cavities without powder evacuation holes, overhangs without support structures, etc. These issues can to a certain extent be solved automatically and/or some solutions can be proposed, but the production process of the updated model must be simulated again (WP4) and the part itself must be simulated as well (WP2).

According to the information provided by Tronrud (see Table 1), within our current HW/SW configuration this is what happens:

- Input: STL file (or STEP/IGS to be tessellated).
- Step (1) produces another STL file. This is currently done with Siemens NX and Magics.
- Step (2) produces an SLI file. This is currently done with Magics.
- Step (3) produces a JOB file (or Jz, if compressed. This contains commands for the printer: laser intensity, movements, heating, etc.). This is currently done with PSW.

Apparently SLI is a binary format which is an EOS-proprietary variation of CLI. The CLI format is documented here [32] and here [33]. In essence, a CLI file encodes the geometry of the slices (set of 2D polygons) and of possible hatches (sets of straight lines).

Open software to handle the SLI format is available here [36], whereas the project that led to the SW is described here [37].

A very nice overview of scanning path generation for EOS-like machines is given in Section 4.1 of Dr. Zeng's PhD thesis [35], who also proposes to simulate the manufacturing process [34] to assess the eventual printing quality.

The PP algorithms to be developed should take into account as far as possible the requirements specified by the stakeholders (see Section 5.4).

7.2 SLICING AND LAYERING TO PROVIDE INPUT TO WP4

In AM contexts, terms such as "slice" and "layer" are sometimes associated to the same concept. However, in WP3 we need to neatly distinguish the planar 2D curves (slices) from the portion of the object enclosed by two consecutive slices (layer). Thus, in WP3 we say that a "slicing" is the process of converting a 3D object represented by its bounding surface into a set of so-called "slices". Each slice is the intersection of the surface with a plane, and the set of all the slices is the set of intersections with parallel planes. Note that a single slice can consist of multiple coplanar curves. The distance between two consecutive planes is called the "layer thickness", and can be either constant or "adaptive". The part of the 3D object contained within two consecutive planes is called a "layer". A process that partitions a 3D object into a set of layers is called a "layering". Note that, while the output of a slicing is a set of 2D curves, the output of a layering is a set of 3D objects whose union is the input object.

In a typical AM pipeline, the slicing process is applied to an STL file, which describes a set of triangles representing a piecewise-linear approximation of the design model: thus, the resulting slices are usually polygons that can be saved to a Common Layer Interface (CLI) file, even if EOS uses a slight variation of this format called SLI.

It is not clear if the software used at Tronrud (i.e., Magics) can export ASCII CLI files to represent both the part and possible support structures. In some EOS documents it appears to be possible, but at Tronrud they could not find a way to do that. ASCII CLI is required by the simulation tools to be used in WP4.

Within WP4 there exist two possibilities to **define the domain** used for the numerical simulation of the AM process (see D4.1 for further details):

1) The first possibility consists of defining a **simple box** that contains the geometry to be built-up using the AM process. The size of the box depends on the actual size of the part including the supporting structures used during the MD process. As a further step, the simulation package will perform the **slicing** of this volume to get a layered domain spitted according to

a **pre-defined layer thickness**. This thickness corresponds to the actual thickness of the material layer sintered by the heat source. The meshing algorithm will generate the **finite element discretization** required for the finite element analysis. Finally, the **scanning sequence** predefined for the machine (**CLI** data in ASCII format is the current option) must be made available to **"activate" the elements** belonging to each layer of the domain. As a result, the final shape of the part produced by AM depends on the material sintering induced by the heat source over the existing powder bed. Similarly, from the numerical point of view, it is possible to start with a large number of elements defining the powder bed for each layer, to be activated (sintered) according to the same scanning sequence of the real process. Hence, the geometry of the model and the definition of the supporting system are not necessary. The mandatory input data is the actual scanning sequence and the layer thickness set for the AM machine.

2) As an alternative, it is possible to **import the CAD geometry** of the expected part to be produced by AM. The geometry of the **supporting structure** must be available too. The corresponding volumes defining both the part and the supporting structure must be **sliced** to get a layered model. Each layer is defined by the polyline (intersection of the original model (STEP or STL triangulation of the surface) with the horizontal plane representing the current powder bed level. The volume between two horizontal planes defines the layer. The meshing procedure will generate the **finite element mesh** necessary for the numerical simulation of the sintering process. Also in this case the **scanning sequence** (hatching sequence) corresponding to the sintering process must be available to activate the element belonging to each layer. Alternatively, the entire **layer can be activated at once**. This simplified method can be convenient either when the scanning sequence is not available or to speed-up the simulation strategy in case of a huge number of layers.

Thus, to perform an accurate thermal and stress analysis, WP4 requires the slices along with the scanning sequence in both the aforementioned solutions. In the second solution, a simplified method can be employed to avoid the need of an exact scanning sequence, though this reduces the accuracy of the simulation. Additional information such as, e.g., the material and other printing parameters, might be necessary in any case.

If the first solution is adopted, WP4 can simulate the actual process without the need of any other geometric information. Conversely, if the second solution is adopted, the simulation uses a layering of the original design geometry, thus requiring the design model as an additional input. However, we observe that WP4 should predict shrinkage and thermal stress-induced deformations on the **printed object**. Such object is fabricated on the basis of the slice geometry, and not on the basis of the original design geometry (the two are normally different). Thus, creating the finite element meshes starting from the slice geometry should lead to a more reliable result.

7.3 INPUTS OF THE NUMERICAL SIMULATIONS TO BE PROVIDED BY PP

Based on the possibilities discussed in Section 7.2, the inputs for the simulation package are the following:

- CAD geometry (STEP, IGES format) of component and supporting structure. Only for the second option.
- Slicing tool. This is used to split the original domain in a sequence of layers.

- Meshing tool. Used to generate the mesh of each layer in between two consecutive horizontal planes representing the powder bed. Minimum one element through the layer thickness.
- Scanning sequence (CLI in ASCII format). Mandatory in case of high fidelity simulation. When the simplified layer-by-layer method is assumed this information is not necessary.

7.4 INTEROPERABILITY

Interoperability along the part development pipeline is one of the main objectives in CAxMan. However, achieving a full interoperability is expected to be a long process, especially if one considers that the design and process planning phases often require the use of third party software tools that the CAxMan consortium cannot modify. Furthermore, the adoption of the new paradigm within the relevant communities will take some time.

On the other hand, some of the problems that emerged from our initial analysis require innovations that CAxMan can bring in a much shorter time. Therefore, our proposal is to advance the state of the art in two parallel directions:

- On the one hand interoperability will be promoted; here we require that material information is correctly encoded together with a continuous volumetric description of the parts. Material information will be forwarded to the AM process simulation done in WP4, whereas the continuous model will be processed by Missler's Topsolid to produce a slicing and, possibly, a tessellation. Since no existing format appears to be directly exploitable for such an integrated representation, we might need to define one, and possibly propose a suitable extension to one of the ongoing standardization efforts in the area (AMF or ISO 10303).
- On the other hand, we need to improve the single steps of PP starting from the current practice as described in this document. Given that the implementation of full interoperability will be a long process, we need an existing baseline to implement the findings that the CAxMan partners will produce in WP3. These contributions will be readily exploitable by the community (e.g. geometry repairing, part orientation algorithms, etc.). Some of these finding, however, will be implemented by considering that they will require an extension to deal with the new interoperable format (once the format is ready and stable).

One of the key issues of interoperability in CAxMan is between design/simulation activities (performed in WP2) and PP (goal of WP3). To clearly separate the domains of competence of these two Work Packages, we have decided to assign to WP2 all the tasks which must be aware of the geometry and material(s) used, but which are not dependent on the specific characteristics of the eventual AM technology. Conversely, WP3 specializes on one specific printer, therefore allowing selection of the proper layer thickness, orientation of the parts, etc. For example, supporting structures, slicing, and slice-based meshing are calculated in WP3, and cannot be produced at design stage because they depend on the specific printer at hand.

Note that the STL format, currently used in AM, does not include material information. Even though AMF constitutes a step forward w.r.t. STL, it is not to be considered the ultimate file format for 3D printing, because it is not powerful enough to encode arbitrarily curved volumetric models. AMF represents boundary models only and incorporates material information. Each "volume" in AMF can be associated to a single material definition. Each material definition has an XML description (without semantics, so graded material can be defined). If AMF is used, a multi-material continuous volumetric representation must be converted to a collection of tessellated volumes (one for each material).

STEP might represent continuous volumetric models as “isogeometries”. An isogeometry encodes a set of volumes, their adjacencies, and additional “fields” that can be used to store material information (without semantics, these fields can be used to specify single or graded materials).

8 CONCLUSIONS

After the analyses of scientific literature, baseline PP and stakeholders' perspectives, the following main conclusions can be drawn:

- The STL geometry repair is a crucial issue and the PP should address both mathematical and physical defects of the parts, possibly producing a feedback for WP2 and/or WP4.
- Volume decomposition and the related issues are not to be addressed with high priority.
- Shape orientation should be optimised for reduction of processing time.
- Support structures should be optimised for reducing the number of defected parts, while keeping the processing time low. The cost of the parts is also a crucial issue affected by the support structures.
- The automatic generation of supports is nowadays unreliable and a good PP must build on the experience of the operator. Proper solutions are required to address this issue by taking into account all the aspects related to the supporting structure (e.g. stability of the part because of the weight increase during manufacture and of thermal phenomena).
- Slicing strongly affects the surface finish but in the CAxMan project this parameter cannot be optimised because of the EOS machine closed setup.
- The toolpath should be generated with the goal of reducing build time, with the feedback of AM process simulation.
- The main KPI identified are:
    - Reduction of material usage
    - Reduction of number of defected parts
    - Reduction of PP time
    - Reduction of build time
    - Reduction of part cost
    - Number of STL-related faults automatically repaired
    - Percentage of useable support structure automatically created/suggested

Finally, it is strongly suggested that the CAxMan Consortium invests in the "ParameterEditor" option of EOS, to fully interact with the machine: otherwise, the default parameters could not be accessed in any way and it would be extremely difficult to implement WP4 findings.

Although a simplified set of numerical simulations of the process can be performed without the scanning sequence, the accuracy of results is expected to be lower; as such, the availability of a CLI file containing the scanning sequence information in ASCII format is considered a requirement for the study.

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