HORIZON 2020

REQUIREMENTS: DESIGN FOR ADDITIVE MANUFACTURING

Deliverable D2.1

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EXECUTIVE SUMMARY

This deliverable collects the requirements of the design for additive manufacturing (AM) stage to be performed in WP2 of CAxMan. This involves requirements with respect to the benefits that AM enables, such as the extra design flexibility that is needed in order to represent inner geometric structures and material properties. It also considers the limitations and interoperability with respect to the later stages of the workflow such as process planning.

In addition to AM, CAxMan will also consider the subtractive process, which is particularly suited to removing material for finishing the objects. The current design process for subtractive manufacturing is described, which serves as a reference when implementing the AM process.

This document extends the Description of Work (DoW) by detailing the methods, data formats and various interoperability requirements for AM. The requirements will serve as basis for the work in Work Package 2 and for the exchange with other work packages.

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1 INTRODUCTION

Additive manufacturing (AM) is a technology that is becoming more and more attractive for production. Also known as 3D printing, parts are materialized layer by layer enabling new types of shapes that cannot be produced with traditional manufacturing procedures. For example, parts can have complex cavities and holes for, e.g., weight reduction. In many cases this cannot be achieved by subtractive manufacturing as the tools may not be able to remove material within the object or to reach positions that are inaccessible because of the tool geometry. AM can be conducted with different materials, such as plastics or metal, thus opening up for a wide range of potential products.

The analysis based design process is in this document represented by the two use cases in CAxMan – the NUGEAR and the mould conception. The input to these processes is expected to be a CAD model designed in traditional CAD software (typically in STEP format). Such representations are often not suited for additive manufacturing applications and certainly do not enable the full benefits that AM has over subtractive processes. In order to prepare the model for printing, several design steps are necessary to define the geometric and other properties like materials, material grading and inner structure. Furthermore, data formats representing this information are required in order to exchange the data between the involved process steps. In addition to the design data, information for and from conducting the simulation are required, such as boundary conditions, source terms and simulation results.

Work Package 2 in CAxMan covers the analysis based design methods for AM processes, and this deliverable describes them in more detail compared to the DoW. Furthermore, this document collects the requirements for the individual steps to facilitate the exchange between them. The requirements will serve as basis for the work in Work Package 2 and for the exchange to other work packages.

2 REQUIREMENTS: DESIGN FOR ADDITIVE MANUFACTURING

In this project, AM will be adopted to improve various aspects of the products for selected use cases. The design process required to support AM will be deduced from the requirements that are collected in this document.

The goal of the design stage is to produce a representation that can be adapted both to the requirements of the objects to be manufactured and the requirements of the manufacturing process. The main focus of CAxMan is on additive manufacturing processes; thus the representations for design must be suitable both for exploiting the benefits of AM (such as design of voids/cavities and material properties) and taking into account its limitations (e.g., some AM technologies, such as those that are powder bed based, cannot have closed voids as the powder cannot be removed). There is also a need to combine additive and subtractive processes in order to optimise the final form of the manufactured object.

In this section, the current workflows for the use cases are described, and the extension to AM is sketched. The further steps and the required information in order to conduct optimisation and process planning, which is done in other work packages, are outlined. The integration regarding what the user interface will look like and how the design process will utilize the CAxMan infrastructure are also discussed.

2.1 NUGEAR

This section describes Use Case 1 of the CAxMan project – the NUGEAR. It outlines typical design workflows along with the expected benefits that AM will bring to the NUGEAR.

2.1.1 Workflow

The NUGEAR design workflow is outlined in Figure 1.

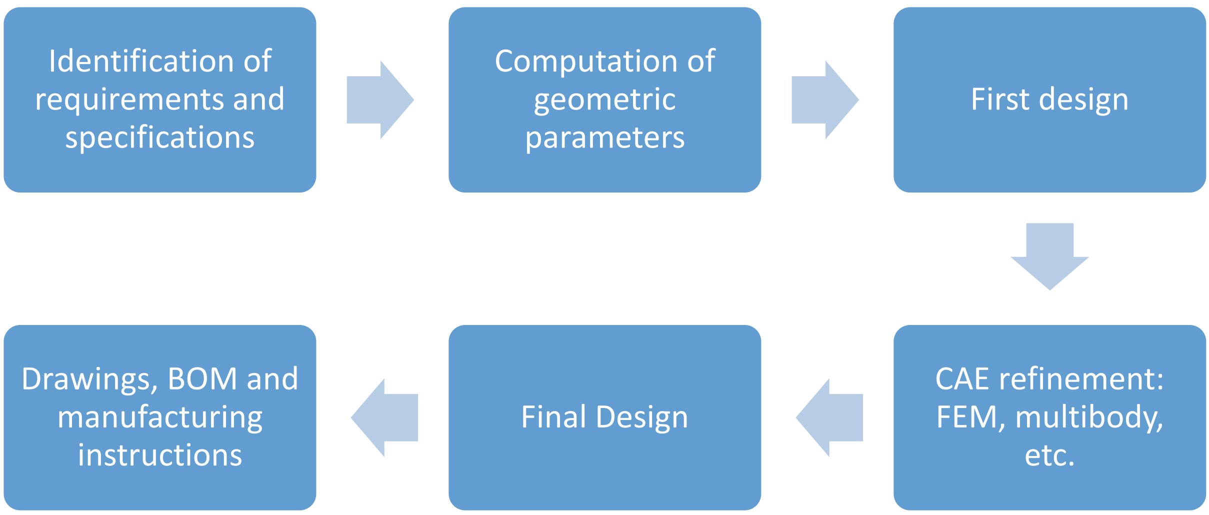

FIGURE 1: NUGEAR DESIGN WORKFLOW.

The first step is of course the collection of the gearbox specifications, which are to be computed:

- on the basis of the power to be transmitted (torque and speed),
- on the use of the gearbox (power transmission, positioning, etc.),

- on the environment where the gearbox will operate (e.g. vacuum, strong magnetic fields, underwater, etc.),
- on the expected operational life,
- on the duty cycles (intermittent or continuous load, shocks, overloads, etc.) and
- on the geometric/dimensional constraints to be met (maximum length or diameter, etc.).

Then, a first attempt of system architecture is drafted on the basis of spreadsheets available at STAM, which allow the computation of the gearbox geometry (gears and shafts).

1. With the chosen speed ratio, the number of teeth of each bevel gear can be computed.
2. The estimated efficiency of the gearbox can be computed based upon the number of teeth of each bevel gear and the global speed ratio.
3. When all these data are calculated, the designer must choose an attempt value for the α angle (inclination of the input shaft); basing on the previous data and the α angle, the other angles of the gearbox can be computed.
4. The pitch cone angle of each bevel gear can be calculated thanks to the relations derived from the kinematic analysis of the gearbox.
5. The stress and fatigue design is performed based on standard engineering formulas, which provide the teeth mean module. These formulas take into account the shock dynamic coefficient, the teeth shape coefficient, the manufacturing tolerances and the ratio between the tensile stress of the material selected and a proper safety factor. The estimation that is provided at this stage is often cautious and smaller gears can be designed. Depending on the need for FEM verification and on the available volume, the designer can decide whether to keep these values or to make a second loop after FEM verification.
6. Now, after the stress and fatigue design, whose output are the gears modules and their face widths, the geometrical parameters of each gear can be computed. The main parameters of a bevel gear are reported in the following Figure 2.

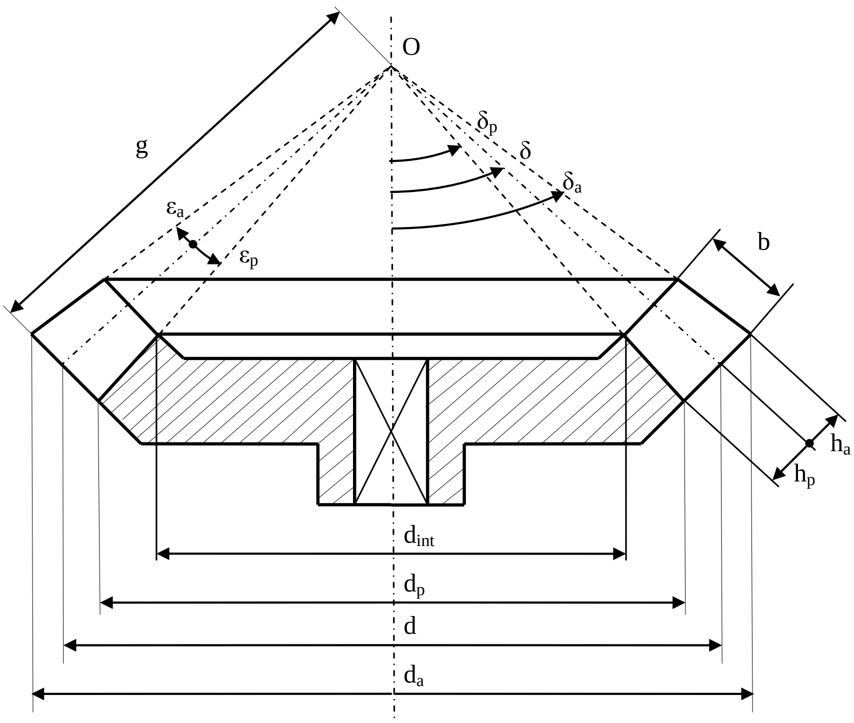

FIGURE 2: MAIN PARAMETERS OF A BEVEL GEAR.

7. Finally, two conditions on the gears' geometries must be taken into account. The first one checks whether there is enough clearance between the teeth, so that the gears can rotate without interference. The second one checks whether the link with two gears (planet link) can be produced: as a matter of fact, the root cones must not overlap. If both of them are respected, the NUGEAR parameters are all computed; otherwise a new α angle must be considered.

In case a multi-stage gearbox is being designed, this procedure must be repeated as many times as the number of stages of reduction.

As soon as a first step of geometrical parameters of the gearbox is available, the CAD can start.

Firstly, the gears are modelled with their blank shape, and the activity focuses on the selection of bearings. In fact, being off-the-shelf parts, the design of the gearbox is strongly driven by the availability of products complying with requirements. Besides, the choice of the bearings also drives additional elements to be designed, such as: snap rings, lock nuts, shaft shoulder and grooves, etc.

The design of the teeth shape (Figure 3) is performed on the basis of a procedure developed by STAM, which follows the kinematics of bevel gears.

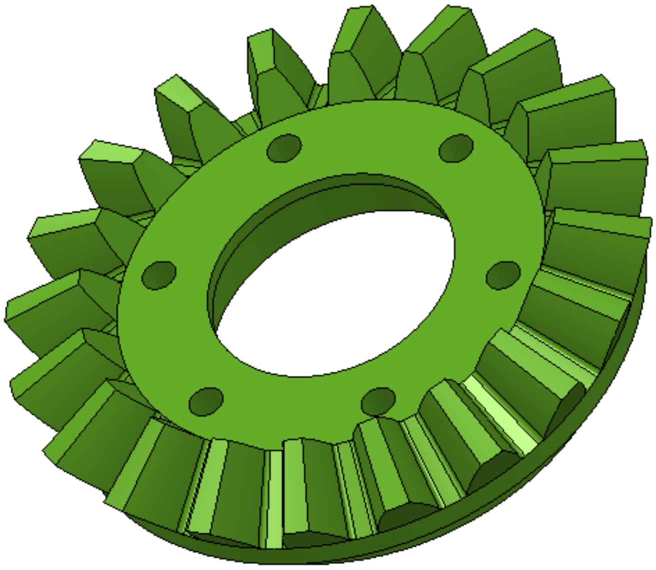

FIGURE 3: TEETH GEOMETRY.

The gear depicted in Figure 3 is a straight bevel gear, i.e. the teeth have a straight shape in the direction of the vertex of the gear. Several other tooth shapes are possible in case of "curved" bevel gears, such as: Gleason, Oerlikon – Spiromatic, Klingelnberg – Palloid, Klingelnberg - Zyclo – Palloid, Modul – Kurvex, etc. In case one of these shapes is to be designed, the section of the vane must follow different curves (spiral, cycloid, involute, arc, etc.) and be scaled according to different rules.

The design of the balancing mass is performed at this stage on the basis of a formula resulting from the kinematic analysis of the mechanism. By varying the weight and the shape of the mass, the inertia characteristics of the input shaft and the centre of gravity of the input shaft + planet link assembly change accordingly. The problem can be solved with an optimisation routine (available in the CAD software), which optimises the two parameters (influencing static and

dynamic balance) according to the topological constraints (dimension and shape of the gearbox envelope, position of the bearings, etc.).

The first complete CAD is the starting point for the simulations. The main simulations that STAM performs on the NUGEAR, to optimise its design, are:

- FEM structural on the gear teeth to verify resistance to nominal load.
- Multibody dynamic to verify the design of the balancing mass.
- FEM structural nonlinear, to verify teeth deformation in case of massive overload (crash load), including strain localization and cracking simulation.

Not all the simulations are strictly required for every design of the gearbox. If the gear dimensions obtained by the stress and fatigue design fit the available volume, the FEM structural analysis on the gear teeth to verify resistance to nominal load can be skipped. Similarly, the nonlinear analysis is done only in case a certain behaviour of the gearbox is expected in case of overloads.

The multibody dynamic verification is made on models made by STAM. Forces and moments are analysed in the revolute joints to verify that no load is transferred to the frame of the mechanism. The only considered forces acting on the system are the inertial forces due to body motion; they give rise to reaction forces in revolute pairs, which are computed by the developed models; contact forces caused by gear pairs are not considered, as they do not affect the studied balancing problem.

The design of the NUGEAR is then refined with all details that were missing: connections with other parts of the mechanism (motor and load); a suitable case with its caps must be designed and seals added according to the lubrication method, etc.

The final stage of the design is the preparation of technical drawings, with indication about the geometrical and dimensional tolerances, surface finish, etc. A Bill of Materials is often provided to identify the COTS components. Finally, instructions are prepared for the workshop in case of special design features.

2.1.2 Additive manufacturing benefits

The NUGEAR design process described so far refers to traditional subtractive processes. Additive manufacturing has not been exploited by the company to produce the gearbox. In this regard, STAM's main expectation from the AM is to develop an industrial manufacturing process capable of reducing the cost of main components of the NUGEAR; this may lead to the successful development of the overall system. In fact, the additive manufacturing technology could be an interesting way to solve the cost bottleneck related to its commercial exploitation.

Another very important aspect could be to develop an appropriate design for manufacturing, in order to perfectly balance the dynamic effects of unbalanced masses, without raising production costs related to production of complex shapes (see Section 7).

In fact, the two components that are characterized by a very difficult manufacturing are the input shaft, where the balancing mass is installed, and the internal bevel gears.

The reduction of component cost is not the only benefit of AM. For different added value applications, such as for the robotic field, the NUGEAR's intrinsic characteristics of multiple teeth engagement could be stressed, as it guarantees high shock/overload tolerance and high reliability.

This aspect could be further improved with a proper optimisation of the mechanical characteristics of the teeth, by optimising their shape for instance. In fact, with conventional manufacturing methods the shape of the teeth cannot be modified, while additive manufacturing allows production of free form parts (see Section 7).

Furthermore, in CAxMan numerical simulations with isogeometric analysis will be conducted, which will improve the shape optimisation loop with respect to FEM.

To summarise, the main benefits envisaged by STAM in the AM are:

- Reduction of parts cost (through a more cost-effective process, through manufacturing steps reduction, through the avoidance of specific tooling)
- Reduction of manufacturing time
- Reduction of parts weight through addition of voids in the volume of the gears
- Increase of efficiency of the gears (namely: reduced surface roughness)

Overall, STAM will use the knowledge generated on innovative production processes, by combining it with the design of the patented gearbox NUGEAR. STAM will benefit from CAxMan's new design approach for AM, which can be applied to the gearboxes developed by the company (including the NUGEAR).

2.2 MOULD CONCEPTION

The aim of this section is to describe the design process and the conception of a mould. The current process and the benefits adopting AM are reviewed.

2.2.1 Thermoplastic injection technology

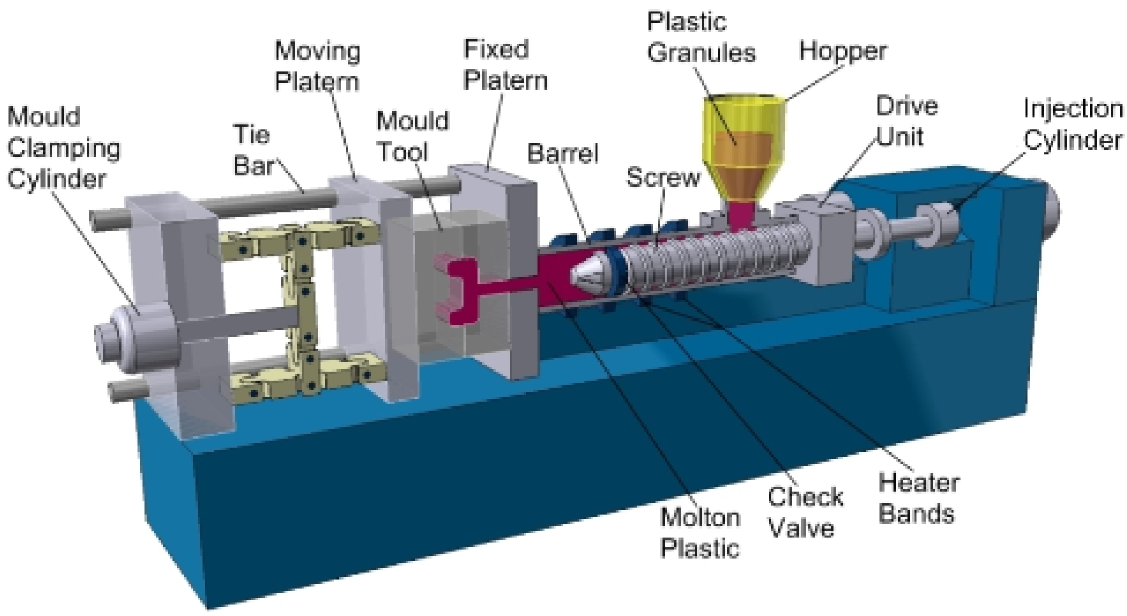

FIGURE 4: PRESS MACHINE DESCRIPTION.

An injection mould is at the core of thermoplastic injection technology. Figure 4 shows a press machine to produce a plastic part. The clamping unit with the moving platern covers the half of

the mould. It opens and closes the mould and supplies sufficient force to keep the mould closed when molten plastic is injected under pressure.

The injection unit takes plastic raw material granules, heats them until molten, and injects them into the mould. Machines consist of a barrel that contains a screw (imagine a kitchen mixer) and the barrel has heater bands around the outside, which raise the temperature to the correct level to melt the plastic. This requires accurate control, as different polymers have different melting temperatures. If the temperature is too low for the particular polymer, then not all of the material will melt. This will result in unmelted pieces of plastic being in the moulding, affecting performance and appearance. Setting temperatures too high could result in plastic degrading, leading to poor appearance and reduced performance. The amount of time that the material resides in the barrel can also lead to degradation, so weight of the part and cycle time become important factors.

The rotating screw forces the plastic along the barrel. This in turn forces the screw back as the molten material collects at the end of the screw. When the right amount of material for the next shot has accumulated the screw stops rotating. The screw then acts like a plunger moving forward and forcing the molten plastic into the mould.

(Source: www.rutlandplastics.co.uk)

2.2.2 Mould functionality

A mould can be divided into five main mechanical functions (see Figure 5):

- F1 is the cavity (how we will mould the part, how many parts in one shot)
- F2 is the injection (how and where the part will be injected)
- F3 is the ejection (how the part will be ejected)
- F4 is the cooling system (how the part will be cooled)
- F5 is the frame structure also called mould base (how the frame will be around the other components)

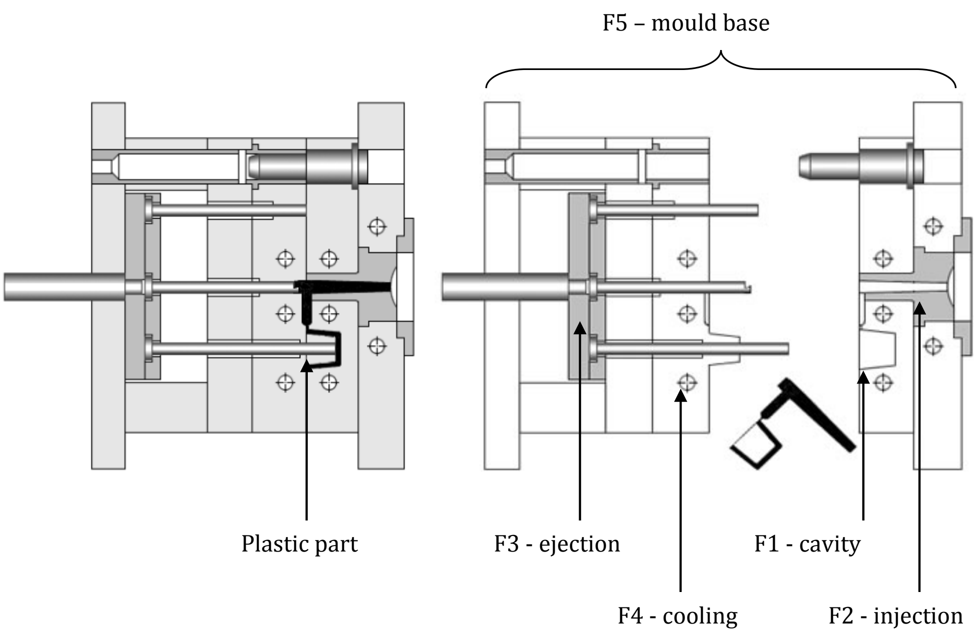

FIGURE 5: MOULD DESCRIPTION.

After been melted into the barrel, the hot material is injected into the mould through the nozzle (F2). We need to keep the plastic hot enough in order to fill the cavity (F1) as quickly as possible. Once the part is completely filled we want to cool the part to reduce the temperature to approximately 60 °C (F4). Then the mould can be opened and the part ejected by the ejector set (F3).

In the following section, the different functionalities are described in more detail.

2.2.2.1 Cavity (F1)

In this function we decide how we will mould the part, what is the main moulding direction and the others ones. For example, if we have to mould a simple glass, there is only one direction, but if we have to mould a box with a hole on the side, then we will have several moulding directions (see Figure 6).

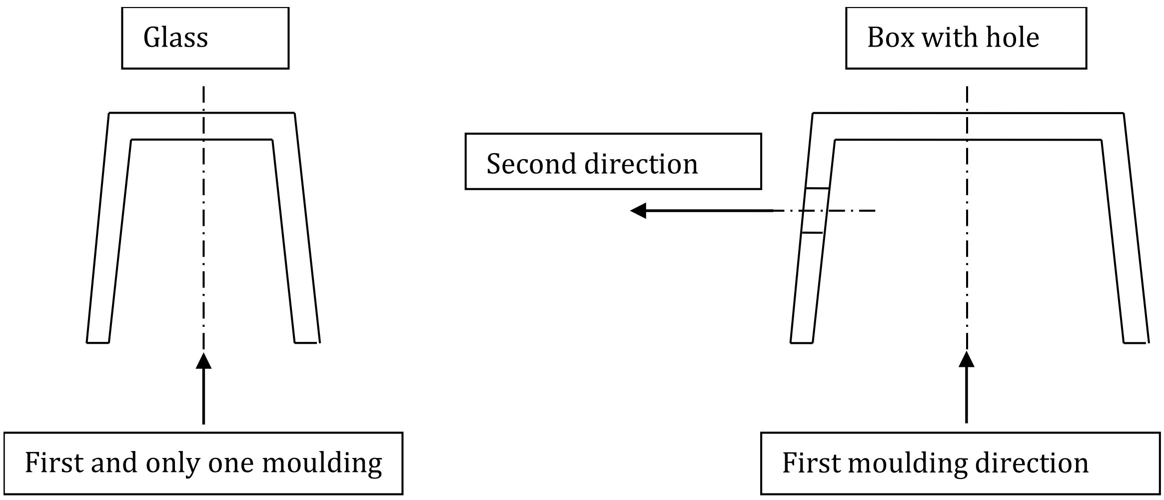

FIGURE 6: MOULDING DIRECTIONS DEFINITION.

When the best way to mould the part is found, we can design the cavity around the part. In a case of a multi cavities mould, one big cavity can include 2 shapes to produce 2 identical parts.

The cavity has to be very resistant because it has to resist the injection pressure (near 500 bars).

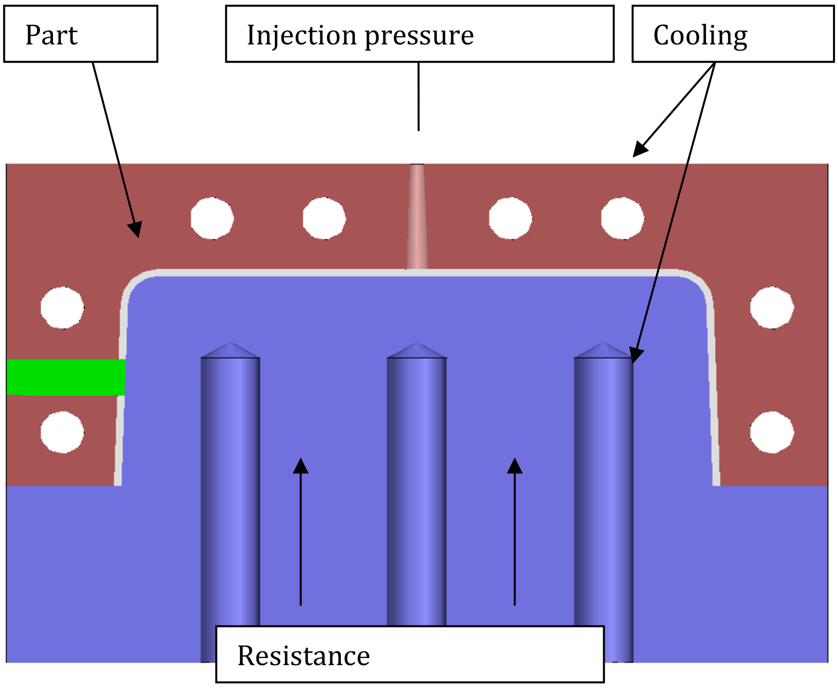

FIGURE 7: CAVITY DEFINITION.

In Figure 7 we can see that the cavity needs to resist against the force created by the injection pressure. The resistance of the cavity block is reduced by the cooling system, generally constructed with holes Ø8 mm. That is why a lot of steel is needed.

Maybe with AM technology, we can imagine a new wire framework geometry to resist the injection pressure.

2.2.2.2 Injection (F2)

To realize this function we use two technologies: Cold runner or hot runner.

Cold runner: This system "carries" the hot material from the nozzle of the machine to the injection point of the plastic part. After the shot the cold runner becomes a waste (recyclable).

Hot runner: The aim is the same as above, but in this case there is a resistance around the nozzle in order to keep the material hot. There is no waste. You produce only a part.

2.2.2.3 Ejection (F3)

When the part is moulded, we must take it off the mould. Related to the shape of the part we have a lot of possibilities to do it. Some examples:

- Slider: When we have a hole on the side of a part we cannot unmould it naturally (see box picture above). In this situation we can put a pin on a lateral slider and remove it before the ejection of the part.

- Threaded pin: When we have a part with a thread (cap for a water bottle) we have to unscrew the component that moulded this shape after the ejection. In this case we use the threaded pin system. This is a pin with a thread and a gearwheel, which traces a helical movement.

- Ejector pins: It is the main solution to get a part out of the mould. Pins are fixed on an ejection plate pushed by the ejection bar of the moulding machine.

- Stripper plate: The technology is used when we do not want to have some mark on the part. A plate ejects the part by its base.

2.2.2.4 Cooling (F4)

As explained in Section 2.2.2.1 the cavity is filled with the melted and hot material (near 240 °C). In Section 2.2.2 we have seen that we have to wait for the temperature of the part to go down to 60 °C. To go down faster we put a cooling system in the mould. Very often the temperature of the water is near the 15 °C to 30 °C range. But care is needed as the cooling system also has an impact on the deformation of the shape after the ejection. The water is flowing through holes, which today are produced by drilling technology.

The AM technology can be very important for this function F4. With traditional manufacturing it is only possible to drill straight, which is often not at an optimal position. With AM we can put the cooling system exactly where we want.

2.2.3 Mould base

The mould base is the support of all the other parts. Its dimensions are linked to the size of the part, the number of parts that will be produced, and to making the kinematics run correctly for the ejection of the part .The mould base is the support of the cores and cavities that will be produced by the AM process. It ensures the rigidity of the mould and the basic kinematic functionality. In most cases, these elements are manufactured with standard dimensions by companies, which are specialised subcontractors. They are able to provide different architectures (number of plates) according to the necessary kinematics to eject the plastic part.

The mould base is composed of many plates (see Figure 8). Each plate is guided with 4 bushes or 4 columns (or more). Mechanically it is statically indeterminate.

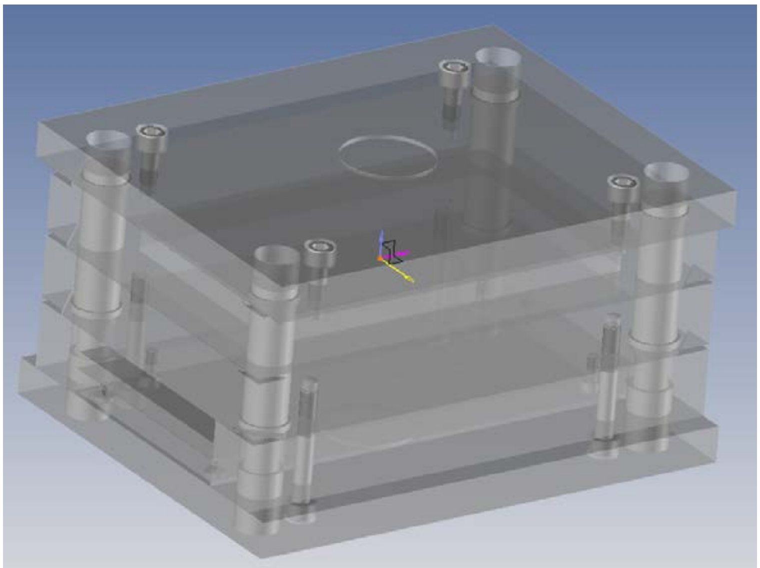

FIGURE 8: MOULD BASE DESIGN.

2.2.4 Design requirement for additive manufacturing

AM is specifically interesting for the production of parts that are in contact with the plastic during the injection process. The main parts where the AM process will be efficient are the core and the cavity.

Two different functions are subject to improvement by AM. The first one is the design and manufacturing of the cooling system; the second one is the optimization of weight and volume of each part.

2.2.4.1 Cooling system

The cooling system is an important part for the injection process, and a better definition of it can make this injection process work more efficiently. The additive manufacturing process permits a better definition of this cooling system. It can be generated by an offset surface based on the definition of the external or internal patches of the surfaces that define the plastic part. This cooling system can be continuous and perfectly paralleled to the cavity and not only straight obtained from a drill operation. The efficiency of this type of thermal regulation is optimal, and it allows a reduction of the necessary tests on a press machine. The thermal analysis tools developed in WP4 will allow checking the design of this cooling system and its efficiency.

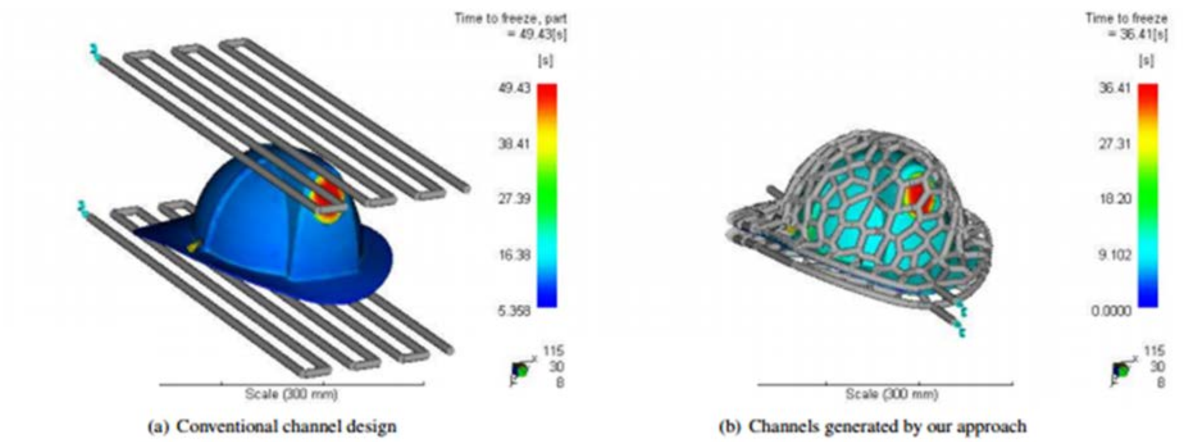

FIGURE 9: COOLING SYTEM DEFINITION.

In order to define this new type of cooling system (Figure 9 b) in a mould, we need dedicated functions in the CAD application to first generate the offset surface where we want to define the water lines, to help the designer to generate the water line on this surface. These water lines can be defined as a pipe or as a cavity.

2.2.4.2 Weight optimisation

Currently the core and cavity are manufactured by removing material by a traditional milling machine, according to the plastic part definition and the cooling system in a block. The additive manufacturing process allows using less material and can be optimised by creating a dedicated “structural mesh”, outside of which material is not necessary. This structure has to be strong enough due to the high level of pressure induced by the injection process. It is paramount to have no deformation in the core and the cavity during the injection.

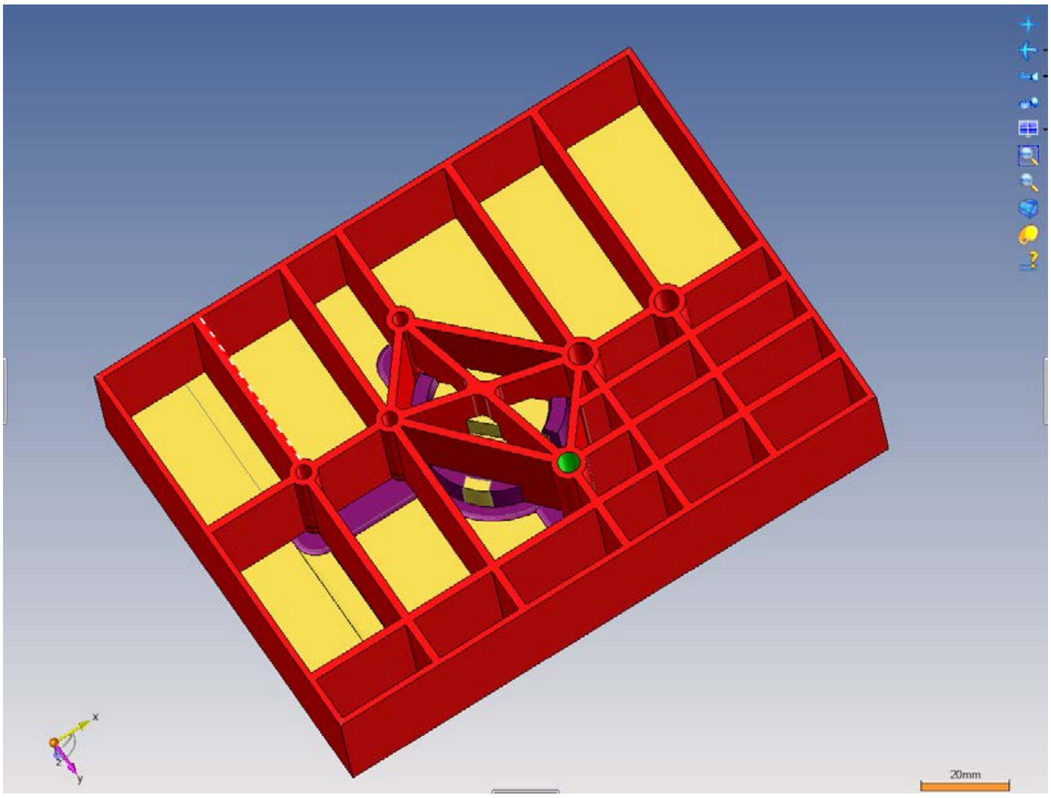

FIGURE 10: CORE CAVITY WEIGHT REDUCTION.

To design a ribbing network as shown in Figure 10, new functions must be develop in the CAD. These functions must take into account a lot of features necessary to the mechanical and kinematical characteristics of the mould (ejectors, fixing, movements, etc.).

2.3 FROM STEP/CAD INPUT TO ANALYSIS, OPTIMISATION AND PROCESS PLANNING

After the design process, additional steps are required for the different phases of the project:

1. Analysis phase: the analysis will be performed using the isogeometric analysis (IGA) paradigm (see Section 6.1) and finite element analysis (FEA, see Section 6.2). This requires the volumetric representation of the geometry (multi-patch or trimmed, see Section 6.1.2) or tetrahedral or hexahedral meshes (see Section 6.2) with the information about the type of material associated to the different parts, the mathematical model to be solved (elasticity, heat transfer, fluid dynamics, etc.) and the appropriate boundary conditions (prescribed displacements, loads, temperature distribution, etc.).
2. Optimisation phase: this task will be performed starting from a suitable parametrization of one (or possibly a few) starting configurations of the geometry, possibly changing the position of a subset of the control points defining the geometry parametrization (we will not perform topological optimisation; see Section 7.1). This requires information about the active control points to be involved in the optimisation (which might be specified indirectly, e.g. the user might just require optimisation of a characteristic length like a diameter or a thickness) and the material properties subject to optimisation. Moreover, the optimisation phase requires information about the objective function to be optimised and on the constraints to be satisfied by the optimised solution.
3. Process planning: the other two phases use continuous representations to encode bivariate or tri-variate objects. The process planning phase exploits the TopSolid software

provided by Missler to convert the continuous representations into tessellated models. Then, these tessellated models are used by Tronrud's software (Magics) to compute the support structures and slices to be sent to the printer. It is therefore required that TopSolid can successfully parse the file formats produced in the other two phases (see Section 3.3).

In order to achieve interoperability, the standard ISO 10303, "Standard for the Exchange of Product model data" (STEP) should be extended in order to address the requirements (WP9).

In order to switch between the different representations, the CAD files must be imported and converted into the respective formats. The envisaged importing process is described in Section 3.1, where CAD data structures are processed to generate a representation for analysis, i.e., the physical simulation of product properties. Two different types of simulation, i.e., IGA and FEA, will be conducted in the project as described above. The conversion between these representations is called meshing in this case and is described in detail in Section 6.1 and Section 6.2.

2.4 USER INTERFACE

As described in the previous section, the workflow consists of many steps and involves many different applications. Each application might require a separate user interface if it depends on user input. Therefore, there will not be one unified user interface to guide through the entire workflow, but individual concepts will be developed that fit the specific tasks associated with each application described in the next section.

2.4.1 Integration into the infrastructure

CAxMan builds on top of the CloudFlow project, where independent and heterogeneous software components are integrated into the same infrastructure and chained together to create continuous self-contained workflows. Therefore, the concept of *CloudFlow Services and Applications* will be used to realize the envisaged design workflow inside the infrastructure. Work Package 1 covers the infrastructure tasks and more information regarding services and applications and their integration can be found in deliverable D1.2.

With respect to the design methods in CAxMan, the required applications will be integrated in the following way:

- **CAD (TopSolid)**
  As CAD applications feature a large set of functionality with a complex user interface, this step of the workflow will be executed as a desktop application on the end user's computer. The link to the infrastructure is realized at the data level, such that the TopSolid software can access the files in the Cloud storage by upload and download. User authentication with Cloud credentials ensure the corresponding access and enable specific AM features.
- **PLM database (Jotne EXPRESS Data Manager)**
  The PLM (product life cycle management) database will be the central place for data storage and sharing apart from the direct Cloud file system. Therefore, it will be deployed as an integrated component inside the Cloud infrastructure and will be accessible for data management by all other services and applications.

- **Subdivision Modelling (IGD Modelling tool)**
  Similar to the CAD application, the software to design voids and cavities based on subdivision volumes will be implemented as a desktop application that runs locally on the end user's computer, as 3D modelling interactions in a web browser are difficult to realize. Data exchange and authentication will be handled via the Cloud infrastructure.
- **Meshing and Simulation (IGA and FEA)**
  Meshing and simulation are usually very time consuming tasks. However, they usually do not need any additional user interaction while the computation is running. This fits very well to the concept of asynchronous services as they are designed in CloudFlow. This concept will be used to integrate these tasks from the CAxMan project. The configuration of the initial parameters will be realised directly through an HTML-based web interface. General functionality to display the current progress and status of long-running operations is already available in the CloudFlow infrastructure.

3 REQUIREMENTS: INTEROPERABILITY TO CAD

The additive manufacturing process is one of the stages in the production of a product. Data that describe that product and its process related attributes need to flow efficiently into and out of this manufacturing stage. Data exchange is, however, not the only data interoperability related requirement. It will also be possible to collect all product description data into a single and consistent data set, which, thus, will contain all data that were accumulated for that product throughout its lifecycle. Such a requirement of a holistic product data representation is triggered by law regulations of product liability, by a wish to reuse data and by the opportunities that capturing of and reasoning over knowledge of a model-based product description might give. The richest product lifecycle data model currently available is specified in ISO 10303, also known as STEP, Standard for the Exchange of Product Model Data. It is a requirement that CAxMan applications use this standard. Support for STEP is part of the CloudFlow infrastructure that also applies to CAxMan; see Section 2.4.1.

Data exchange and data integration are, thus, high level, product data related requirements applicable also to data that describe the additive manufacturing related characteristics of a product.

Data interoperability requirements can be divided into requirements of the semantic contents (that is, what is the meaning of the data) and requirements of data representation (that is, how do the data appear on a file or in a database).

Applications for additive manufacturing will need to support (that is, read and/or write) one or several of the following AM formats to exchange data with processes that feed into (CAD, CAE) or read from AM (CAD, CAE, NC-machines):

- STL – STereoLithography (Creo3, SolidWorks, etc.); see Section 3.3.1
- AMF – Additive Manufacturing File (SolidWorks, Catia (planned), etc.)
- 3MF – 3D Manufacturing File
- ISO 10303-21 – STEP physical file format (most CAD systems (AP242), some CAE systems (AP209), some CAM systems (AP238)).

A product that shall be or has been produced by additive manufacturing technologies needs to be described by the following product characteristics:

- Shape representation (CAD; AP242)
- Geometric dimensioning and tolerancing of shapes for manufacturing (CAD; AP242, AP238)
- Presentation, such as colour and surface texture (CAD; AP242)
- Material (CAD, CAE, material databases; AP242, AP238)
- Manufacturing instructions (CAM; AP238).

Requirements are derived for some of these aspects in the following sections. See also Section 6.2 for details concerning input data for the numerical simulation of the AM process.

3.1 INPUT FORMAT (STEP READER)

STEP addresses all of the above mentioned five product characteristics. However, additive manufacturing requires new concepts to be defined for these characteristics, such as heterogeneous materials, lattice structures and new types of manufacturing instructions. These

will need to be added to the existing standards and subsequently be supported by AM software applications.

The following two currently existing and from ISO available STEP Application Protocols are most relevant to integrate the new concepts into their product models:

- ISO 10303-238 (AP238): Application interpreted model for computerized numerical controllers
- ISO 10303-242 (AP242): Managed model-based 3D engineering

Most likely, AP238 will be merged into a future edition of AP242.

3.1.1 Boundary representations

The following types of shape representation are considered relevant input from CAD to additive manufacturing:

- Exact B-Rep (widely used in industry as STEP or JT)
- Tessellated (widely used; many formats, also STEP)
- High order tessellation (proposal available for AP242ed2)
- Parametric (seldom used for data exchange; model exists in AP242ed2)
- Voxel (intended for inclusion in AP242ed2, but not confirmed)
- Tri-variate NURBS model with block topology (added to STEP by EU-project TERRIFIC[1]); see Section 4 and Section 6 for details.

(Source: PDES, Inc., STEP AP242 edition 2 Additive manufacturing working group)

3.1.2 Material properties

Material is a wide field. Different standards address different aspects, such as material properties, measurement conditions of such properties, material names, material compositions, material production processes and so on.

Material identification and material properties including the conditions of their measurement are in scope of AP242ed1 already. Extensions for AP242ed2 will include descriptions of mixed material.

The following characteristics are candidates for inclusion into future editions of AP242:

- Graded material
  - How the graded material is defined:
- Direction x,y,z, …
- Mathematical expression
- Porous materials
- Stochastic materials

(Source: PDES, Inc., STEP AP242 edition 2 Additive manufacturing working group)

[1] FP7-2011-NMP-ICT-FoF-284981, http://www.terrific-project.eu

3.1.3 Geometric dimensioning to unique AM features

Manufacturing tolerances need to be applied to unique AM features. They are defined in CAD and exchanged to AM applications and machines. The following will need to be considered by the project:

- Free-form complex surfaces, lattices, internal features, embedded components
- Specification of design intent
- Build direction, layer thickness, wall thickness, boundary between materials, surfaces that cannot have supports

3.1.4 Manufacturing instructions

Manufacturing instructions include, among others, the following build information:

- Build orientation
  - Direction vector associated with part
  - ISO/ASTM 52921 definition of AM coordinate systems for build plates and parts
- Build plate size
  - XY dimensions of plate
  - ISO/ASTM 52921 definition of AM coordinate systems
- Build plate placement
- Build volume (add height to build plate)

3.2 DIFFERENT TYPES OF MODELS

With reference to the NUGEAR design workflow (Figure 1), STAM normally works with three versions of the model:

- The complete and fully detailed model, which is the starting point of 2D technical drawings.
- The simplified model for FEM/IGA analyses: this model is de-featured and includes only a portion of the gear (tooth segment). Either one (Figure 11, left) or two gear couples (Figure 11, right) may be simulated at the same time, depending on the goal of the analysis.
- The simplified model for multibody analyses, which includes only two bodies (assemblies): the input shaft (Figure 12, in blue) and the planet link (Figure 12, in green), with the related portions of bearings.

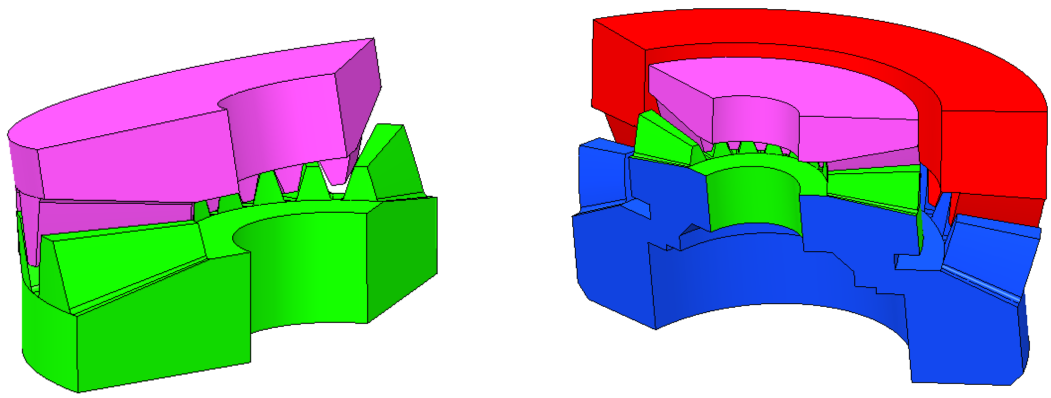

FIGURE 11: SIMPLIFIED MODELS CONSISTING OF ONE (LEFT) AND TWO (RIGHT) COUPLE OF GEARS.

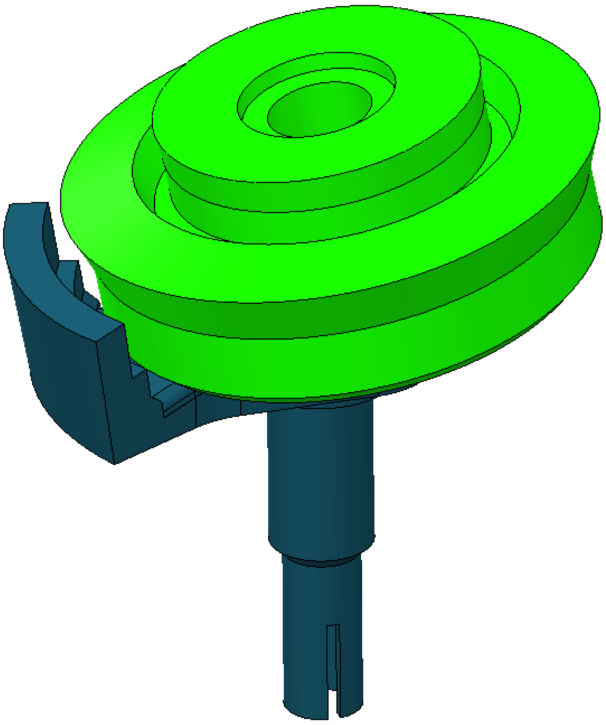

FIGURE 12: SIMPLIFIED MODEL FOR MULTIBODY ANALYSES.

3.2.1 Requirements

The requirements of STAM's models for different purposes are:

- The simplified model for FEM/IGA analyses is aimed at evaluating the shape of the teeth. Therefore, the most important information of this model is the tooth shape and this detail cannot be simplified in the model. Any other detail that does not affect the structural behaviour of the parts can be neglected in order to speed up the simulation.
- The computation load of multibody simulations does not depend on the geometrical details of the parts, so they are not de-featured for these analyses. The bodies that do not affect the dynamics of the system (i.e. static parts and intrinsically balanced parts) are not considered for simplification, but their presence would not affect the computational time.

3.3 OUTPUT FORMAT(S)

3.3.1 Boundary representations

STL models can be used at the beginning of the project to establish a baseline where the software that is currently available in the consortium is exploited as it is. Some improvements can be achieved in later stages by adopting the AMF format because it includes basic components to specify materials. However, currently even AMF can only represent boundary surfaces, therefore we need a tighter integration in the long term.

3.3.2 Tri-variate model for slicing

Almost all existing additive manufacturing workflows rely on the conversion of CAD geometry to STL format for slicing. The STL format requires a discretisation of the smooth geometry so that it can be represented as a soup of triangles. Moreover, these triangles are limited to boundary representations of the outer and possibly inner shells of the model. Thus, a great deal of geometric and material information that could potentially be preserved throughout most of the process is lost on conversion to STL. In addition, for printing with plastics, it is fairly common to define regular internal lattice-type structures at the slicing stage, meaning that there is no precise geometric definition of the internal structure until late in the process. This would in turn result in limitations for the work of WP2-WP4 where precise geometric models are required. However, this is not a major issue for the metal printing considered in CAxMan.

In order to remedy these issues, we propose slicing the tri-variate model directly, which will result in much better preservation of the original geometry together with material distributions. It will also allow the internal structures/voids to be defined at the design stage and to be taken into account in the analysis of WP2 and WP4 and process planning of WP3.

Functionality for planar intersection of boundary represented models exists in SINTEF's GoTools library, but would need to be extended to volumetric models for the purposes of CAxMan. The utilisation of the geometry slicing for the purposes of process planning must also be discussed. This requires a decision on how the slicing information will be shared within CAxMan. Initially, WP4 will use CLI files (common layer interface) in ASCII format to perform analysis of the process, but there is a need to analyse whether this format is suitable for the more advanced requirements of direct slicing of the geometry from WP2.

3.4 MODEL REPRESENTATION FOR DIMENSIONAL METROLOGY

The aim of dimensional metrology is to evaluate the quality of the produced part in terms of its shape and dimension regarding the specification developed during the design of the product. For that purpose, a sampling of the part surfaces in 3D coordinates can be made using one or a combination of the following different technologies: tactile probing using a coordinate measurement machine (CMM), non-contact scanning using a 3D optical scanner, photogrammetry, etc. The result of this sampling is what is called a cloud-of-points (COP), which is a list of 3D points representing the real shape of the manufactured part with high accuracy. The COP can be utilized as the input for the metrology software in order to perform two types of calculations:

1. Extraction and evaluation of the relevant geometries in the part, and comparing these geometries with the nominal geometries and their tolerances (Geometrical Dimensions and Tolerances - GD&T).
2. Reconstruction of the surface, and comparison of this surface with the reference surface of the CAD model.

In Case 1, the result is a set of geometries with their nominal values, their actual values, and the deviations compared to the allowed tolerances.

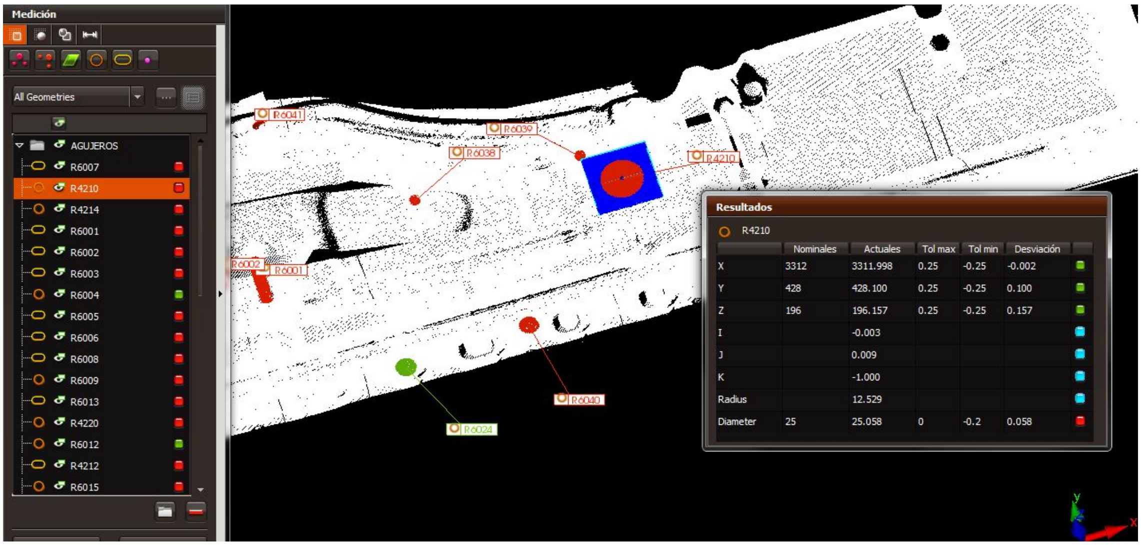

FIGURE 13: EXAMPLE OF EXTRACTION AND EVALUATION OF A CIRCLE FROM THE COP.

In Case 2, the result is a 3D deviation map representing the deviation in each region of the part surface between the nominal model and the actual part. A typical way of representing this map is by using a coloured codification of the levels of deviation (colour-mapping).

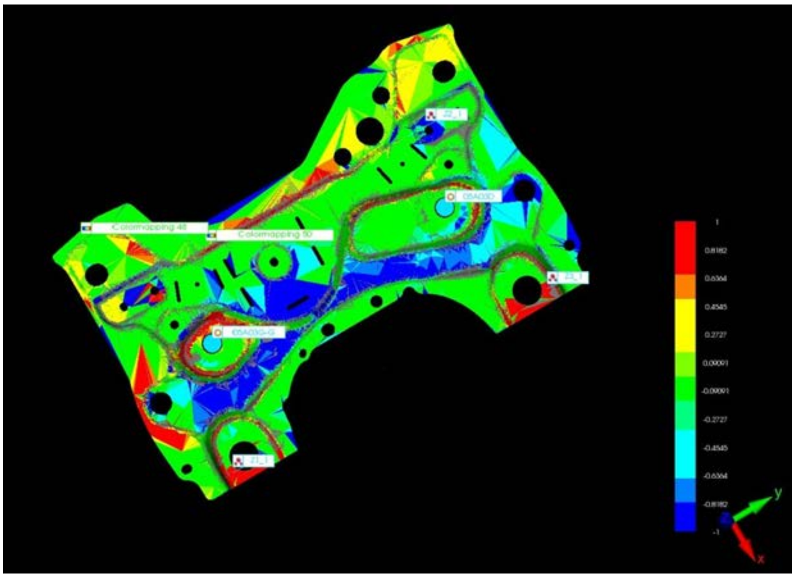

FIGURE 14: EXAMPLE OF DEVIATION MAP: GREEN INDICATES IN TOLERANCE, RED AND BLUE INDICATE OUT OF TOLERANCE.

The data format requirements of Case 1 or GD&T are presented in Deliverable 5.1.

In Case 2, or deviation map calculation, a workable representation of the model surfaces is required that can be utilized to compute the distance between each point of the COP to the model. In general, there are three main types of supported formats:

- Polygonal mesh representation: the most usual format is STL.
- NURBS: it is also possible to represent the model as NURBS. The most common formats are STEP and IGES.
- Parametric surfaces: using mathematical representation of geometries. The most common formats are STEP and IGES.

For the purpose of the project, the representation of the model for metrological deviation map calculation can be STL, STEP or IGES.

The tri-variate shape representation of the model surfaces is not a format that is utilized in dimensional metrology. Nevertheless, further exploration of potential use for deviation map calculations can be performed during the project.

4 REQUIREMENTS: TRI-VARIATE SHAPE REPRESENTATION FOR DESIGN AND ANALYSIS

In this section we discuss the main requirements for the tri-variate model in CAxMan. First a summary of the identified requirements is provided, followed by the background for the requirements:

- The initial STEP model should have good quality obeying the tolerance provided in the model, and many small surfaces in the geometry description should be avoided.
- User interaction may lead to an improved block topology of the tri-variate model. A simple user interface can provide the user with a tool to specify some corner points in a block structured model and also modify curves between boundary surfaces of adjacent blocks. Functionality to help identify matching boundaries of volume blocks is necessary for the subsequent isogeometric analysis.
- The number of blocks in the tri-variate models should be kept to a minimum, and the regularity (non-singularity, good aspect ratio) of the block parameterization should be guaranteed along the design process.
- Refinement routines for the block parameterization that preserve mesh compatibility should be provided.
- Tools for visualization are required to allow for user involvement in the block structuring process and for quality control of the model.
- The expected complexity of the CAxMan use cases (e.g. the elaborate cooling channels in the injection mould) indicate that a pure block structured tri-variate NURBS model may not be feasible. In particular some form of trimmed volumes must be expected. CNR-IMATI's IGATools software will need to handle such models. The actual format for the more flexible tri-variate models must be agreed upon when we have obtained more experience with the CAD models describing the use cases.
- There are feedback loops from WP3 and WP4 to WP2 indicating that there might be a need for changing the geometry. We expect these change requests to come in the format of points/curves/surfaces that the tri-variate model should adapt to or some modified B-spline coefficients implying that nearby coefficients also will need to be changed in order to maintain a good parameterization of the model. The actual format of this revision request must be specified, so that the consequences can be taken into consideration at an early stage of the implementation.
- LR B-spline surfaces and volumes will be included in the geometry formats of the tri-variate model to allow for greater shape flexibility. These formats must be handled by subsequent processes. In the context of isogeometric analysis this will require that a tool for Bézier extraction on these geometries is available in GoTools.
- Subdivision volumes/surfaces will be integrated into the tri-variate model either by continued block structuring or as trimming volumes. New tools will be needed for this integration.

4.1 PARAMETRIC MODELS

Parametric representations of curves and surfaces are ubiquitous in modern CAD systems, traditionally dominating other representations such as implicit or subdivision methods. While implicit and subdivision representations are both very active areas of research (particularly for the needs of additive manufacturing), the main geometry representation in CAxMan will be parametric. This will enable CAxMan to directly support existing CAD tools and will thus enhance interoperability.

Parametric curves, surfaces and volumes embedded in Euclidean space are defined by a mapping from a parameter domain to the Euclidean space (often referred to as the ambient space). The parameter domains are normally path-connected compact sets (bounded and closed) and in the case of splines (see Section 4.1.2) are often given by a product of univariate intervals.

There are several ways to model three-dimensional geometric objects with parametric representations, but the most common method is to model a volume by its bounding surfaces (B-rep). This is the expected input to WP2 in CAxMan. B-rep gives a sufficient degree of flexibility to model the outside surfaces of an object, and it is suitable for traditional subtractive CAM processes such as milling, where the machining tools are limited to removing material on the outside of the object. However, B-rep was not implemented with a view to providing a description of the internal geometries and properties of the model. By enabling a much wider array of objects to be fabricated, additive manufacturing has established a greater need for modelling the internal geometries of an object, as well as its outer shell. This need has also been highlighted in the isogeometric analysis literature – a complementary tool to finite element analysis.

The approach to be taken in CAxMan is to convert the B-rep STEP input to a tri-variate parametric model. This will provide the possibility to model material properties that vary throughout the volumes and the ability to model voids/cavities. The process and requirements for converting from B-rep to tri-variate representation will be described in the next section.

4.1.1 From B-rep to tri-variate

A CAD solid imported from STEP will be represented by its outer and possibly inner boundary surfaces. In addition to the need for a representation of model properties that vary throughout the designed object, the mechanical analysis of WP2 requires a tri-variate model. In this context isogeometric analysis with IGATools will be applied, thus a tri-variate block structured NURBS model will yield an appropriate format. When passing from the boundary representation to the tri-variate model, it will be necessary to define some criteria to assess that

1. the tri-variate model corresponds to the original one, up to a certain tolerance,
2. the tri-variate parametrization is suitable for analysis.

Some preliminary ideas to define these criteria are given below.

Even though CAD models and the types of shape models that are fit for isogeometric analysis are based on the same mathematical framework, namely the NURBS format, the use of this framework differs. In CAD, boundary represented models with trimmed surfaces are heavily used. The surfaces can be of NURBS type, but can also be lower order algebraic surfaces like cylinders and spheres or functional surfaces. In isogeometric analysis, non-trimmed NURBS surfaces and volumes are desirable, although other solutions like the boundary element method and immersed boundary method are also pursued.

IGATools is able to handle multi block tri-variate NURBS models. The blocks must meet in a corner-to-corner configuration, i.e. no T-joints are allowed. Conforming grids (resulting in matching coefficients) on both sides of the block boundaries are preferred, but this is not a required property. In the case of non-conforming grids some appropriate gluing technique must be used in order to impose continuity among blocks, e.g. mortar or penalty methods. Regardless of the conformity of the gluing, the input file describing the geometry must contain information about connectivity of the coefficients on each side of the interface. However, note that this information is only needed for the analysis/optimisation phase, and not for the process phase.

The challenge of generating volumetric block structured NURBS models from B-rep CAD models is not solved, yet. It is related to the generation of block structured models for analysis with the difference method and even to hex meshing [1]. Here the state of the art involves some degree of user interaction. In CAxMan, our aim is to automatically or semi-automatically create models fit for analysis with IGATools. A mainly automated method that can benefit from user input at certain stages in the process is envisaged. The aim is to create a block structured spline model (NURBS or LR B-splines), but we foresee a need for a more flexible format, possibly including trimmed volumes. This may also influence IGATools.

The translation or remodelling from a boundary represented model to a tri-variate, block structured one is a non-trivial task. How it can be approached, depends on the properties of the initial model. Some strategies are:

1. Divide the model in concave edges to reach a template shape that can be handled [2].
2. Reduce the dimensionality of the problem by computing the medial axis or medial surface of the initial model.
3. Build a tri-variate block structured model from a block structured boundary shell where corresponding blocks at opposite sides of the model are combined. This approach is mostly suited for 2.5D models or models that have a (possibly varying) projection direction that can be identified.

GoTools, which will be the tool used in this remodelling, already has some support for the third approach. This strategy will be developed further and combined with other strategies as appropriate to be able to handle the CAxMan use cases.

The generation of a block structured tri-variate model can be divided into topology decision and geometry creation. The model topology will govern the entire construction. Even relatively simple CAD models can give rise to complex block topology, as illustrated in Figure 15.

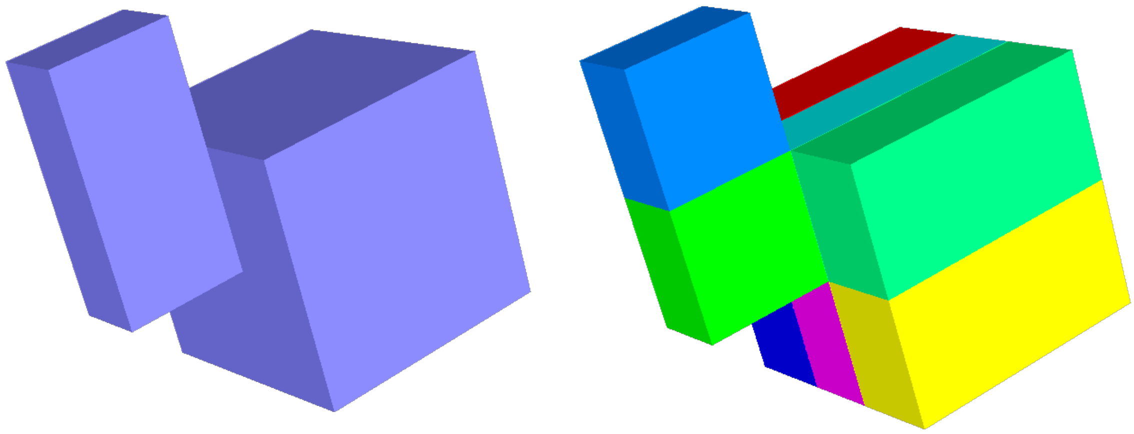

FIGURE 15: A BOUNDARY REPRESENTED CAD MODEL CONSISTING OF TWO BOXES PARTLY ATTACHED TO EACH OTHER IS TRANSLATED INTO A MULTI BLOCK TRI-VARIATE SPLINE MODEL WITH 8 BLOCKS.

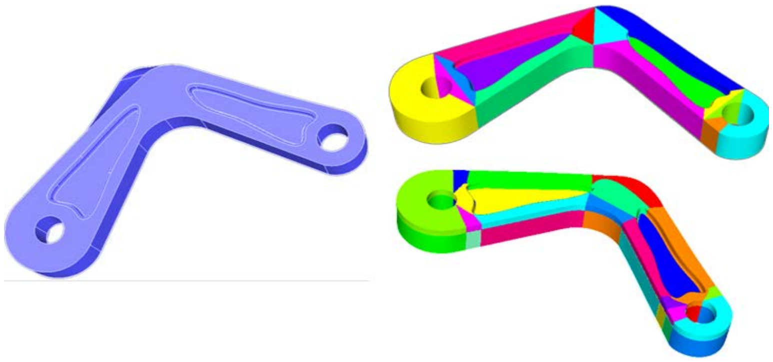

FIGURE 16: TWO ALTERNATIVE BLOCK TOPOLOGIES FOR THE TERRIFIC PART.

There is not one unique solution to how the block topology corresponding to a CAD model should be defined. Figure 16 shows two different approaches applied to the demonstrator model of the TERRIFIC project.

Both the solutions shown in Figure 15 have their pros and cons. The following list determines some desirable properties for a block structured model:

- It avoids extraordinary points, or singularities, in critical areas (the location of critical areas depends on the analysis at hand).
- It avoids block boundaries in critical areas.
- The remodelling typically implies an approximation, but the structure needs to allow good accuracy compared to the initial model. This can imply that constant parameter curves in the initial model should be constant parameter curves in the tri-variate model as well.
- The constant parameter curves in the tri-variate model should correspond to flow lines for the desired analysis. Again these criteria depend on the current analysis.
- The model should have well-shaped blocks and elements (B-spline patches).

Thus, the ideal structure is to some extent dependent on the planned use of the model. Geometric criteria alone are not sufficient.

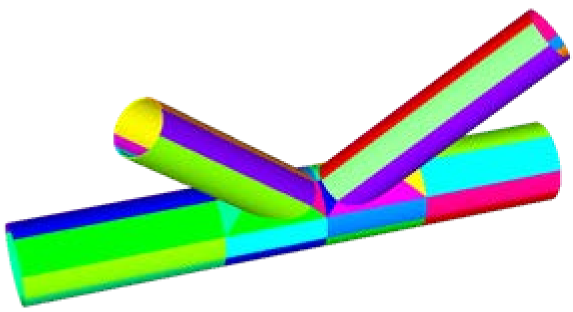

FIGURE 17: BLOCK STRUCTURED TRI-VARIATE MODEL OF A PIPE JOINT.

In Figure 17, it is important for the block boundaries to follow the cylinder axis direction to avoid poor accuracy and wiggling geometry. In this case, an adaption to the constant parameter directions of the initial geometry is beneficial. In other cases, the initial model contains bad parameterization that we do not want to carry on. In the area between the two attached pipes, there are some blocks that tend to be too close to triangular. In general, it can be a problem that an automatic approach for topology decision yields a feasible solution, but not necessarily the best one. We want to include some simple user interaction in the process in the form of a definition of extraordinary points, quality control and modification of block boundaries. The

latter will typically be applied to a block structured outer shell before the volume definition and volume generation will take place.

In general, the quality and properties of CAD models vary greatly. In order to make a good block structured model it is important to be able to perform geometric reasoning on the model. This aim is simplified if the model mainly consists of large surfaces carrying significant information.

Use Case 2 of the CAxMan project includes cooling channels, and, thus, there is an ambition to construct models with voids. Such models can impose a complex block structure, and the block generation process may be challenging. We will consider the use of trimmed volumes resulting from Boolean operations as a tool to simplify the final structure. The main shape is represented by one tri-variate model with well-behaved blocks while the pieces to remove are represented by another set of block structured tri-variate models. More discussions will be required to find a good format for this kind of models. IGATools currently provides basic quadrature schemes that may be useful to handle trimming in analysis; see Section 6.1.2 for more details on trimming approaches for analysis.

An accurate adaption to the initial model by the volume blocks and at least C^0-continuity between adjacent blocks while maintaining a moderate data size are crucial. As a means of achieving this, the pool of allowed spline formats will be extended with locally refinable splines, in the form of LR B-spline surfaces and volumes.

4.1.2 Spline representations

As splines representations are an integral part of the work in WP2, we will provide some details of spline technologies in this section.

Splines, and their rational counterpart NURBS (non-uniform rational B-splines), are a well-established format for representing smooth curves and surfaces in CAD. They make up a large proportion of the representations included in STEP standardised models. Splines are made up of piecewise-polynomial segments/patches that preserve a given level of continuity between the patches. They provide intuitive methods for design by enabling a manipulation of control points that guide the shape of the curve/surface. NURBS provide extra flexibility by allowing weights to be assigned to each control point. They also have the advantage that common primitives, such as circles, cylinders and tori, can be represented exactly. In CAxMan, there is a need to model CAD geometries with volumetric splines/NURBS as opposed to just modelling the boundary with surfaces.

4.1.3 Spline curves

Spline curves, of a given degree and embedded in three-dimensional Euclidean space, are defined by a so-called knot vector (a non-decreasing sequence of real-valued numbers) and associated control points in the ambient space. The knot vector defines the interval of the real line that is to be mapped to the ambient space as well as the order of continuity between the interval segments. The control points are given by positions in Euclidean/ambient space that define the geometry of the curve. Knots can be added (in a procedure known as knot insertion) to provide extra control points and thereby extra design freedom. For NURBS curves weights are also associated to each control point as mentioned above.

4.1.4 Tensor-product splines

The simplest way to extend the curve definition to surfaces (and higher dimensional volumes) is via a tensor-product operation. This defines the spline surface as a mapping from a rectangular parameter domain in 2D, or a hyper-rectangular domain in higher dimensions, to an ambient space which describes the function/geometry. With tensor-product representations, the spline can be decomposed into a product of univariate splines in each orthogonal direction. Tensor-product spline volumes were used in TERRIFIC to make block structured tri-variate representations for isogeometric analysis. A similar approach may be appropriate in CAxMan.

Tensor-product splines are well established in CAD and are included in the STEP standard; however, they also have some drawbacks. The main drawback is that any knot inserted in a single parameter necessarily covers the entire domain in all other directions. This results in a global increase in data size even when only local flexibility is required. Similarly, if knots are inserted to change the order of continuity in a certain region, this change will pervade throughout the parameter domain. In the past decade, techniques to resolve this issue through local refinement have been explored.

4.1.5 Local refinement of splines

In order to avoid the global increase in the amount of data that is seen with tensor-product surfaces, several techniques for local refinement of splines have been proposed. These include hierarchical splines [3], T-splines [4] and LR B-splines [5]. LR B-spline functionality is included in the SINTEF GoTools C++ library; we may make use of (and extend) this library in CAxMan.

Locally refined splines have several advantages that can be utilised in the CAxMan project. These include:

- Stitching together block structured NURBS models into a single model for increased orders of continuity;
- Local refinement of the geometry for IGA (see Section 6.1).

Bézier extraction is a convenient tool for pre-processing spline models, including models using LR B-splines, for isogeometric analysis. IGATools can, with the use of Bézier extraction, handle LR B-spline surfaces and volumes. In order to perform refinement on such models, however, a tighter coupling will be required.

4.2 VISUALISATION OF VOLUMETRIC SPLINE MODELS

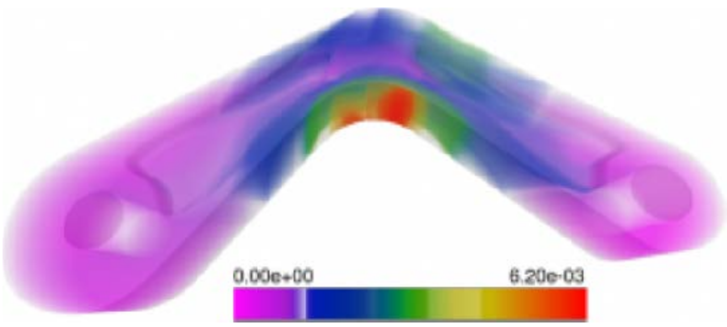

FIGURE 18: ISOGEOMETRIC VOLUME VISUALISATION.

In order to provide intuitive methods for distributing both voids and material properties within the volume, volume visualisation methods are necessary.

Figure 18 shows a visualisation of the stress of an object under external forces. It is foreseen that such information could be used within CAxMan to provide a designer with knowledge of which regions to add/remove the voids/cavities, or alternatively, to vary the material properties.

The visualisation technique in Figure 18, which combines pixel-accurate rendering with order-independent transparency, was developed by SINTEF during the TERRIFIC project, initially for tensor product splines. The software will be extended to include LR B-splines within the scope of the VELaSSCo[2] project. In addition to the deployment on the CAxMan infrastructure, there may also be a need for adaptations to the software within CAxMan, depending on the chosen methods of manipulating material distribution/positioning of voids and the performance needs.

[2] http://www.velassco.eu/

5 REQUIREMENTS: MODELLING VOIDS WITH SUBDIVISION VOLUMES

To realize the positioning of voids within the models in the CAxMan project, subdivision volumes are used in addition to NURBS. Subdivision volumes transfer the general concept of subdivision surfaces like Catmull-Clark [6] or Loop [7] subdivision surfaces into a volumetric representation. In contrast to surface representations, volumetric subdivision algorithms always result in watertight and manifold meshes while still creating smooth and organic surfaces. Approaching the modelling of voids as “negative volumes” inside the object, the decision to use a volumetric representation is logical.

The following sections describe how voids and cavities will be designed using subdivision volumes and how they will be placed inside the existing object. As the final step, they have to be integrated with the tri-variate volume description of the surrounding object in order to maintain a single, consistent representation for simulation and printing.

5.1 REQUIREMENTS FOR MODELLING VOIDS AND CAVITIES

Whereas some additive manufacturing processes (e.g. those based on material deposition) allow for closed voids to be manufactured, this is not generally the case with today's technologies. The powder bed methods that are used by CAxMan partner Tronrud require that the unsintered powder that is deposited inside the object can be removed by some method. In addition, some processes will also require support structures to be manufactured inside the voids in order to support the part of the object to be manufactured above the void. If such structures will be difficult or impossible to remove, their presence must be taken into account in the design stage, as they will most likely have an effect on the functional properties of the object.

5.1.1 Removal of powder for powder bed manufacturing

Powder bed manufacturing methods, such as those used by Tronrud, have the advantage that the need for support structures is reduced – the powder deposited at each layer provides a natural support for structures up to a certain density. This, however, poses a challenge for the weight reduction objectives of CAxMan, since manufacturing closed voids would result in the powder being trapped inside. This must be taken into account at the design stage, as making powder removal channels could have significant effects on the properties of the object (e.g. structural).

One solution could be to disallow any closed voids at the design stage. For the machine available at Tronrud, the requirement is that all internal cavities/pockets have at least 2 holes (with a minimum diameter of 1mm). Compressed air is fed in through one hole and a vacuum cleaner on the other hole is used to remove the trapped powder. This operation should be done before the part is removed from the baseplate, since no powder can be present during heat treatment. However, enforcing this requirement would lack support for other AM technologies (e.g. material deposition based) that can already include empty voids, as well as future developments of powder bed technologies that could solve the problem. A better solution might be to add optional powder removal channels for any closed voids. Steps to optimise the size, number and position of the channels in order to maintain the functional properties of the object could be included in the design optimisation loop.

5.1.2 Integration of non-removable support structures into the design

It is important to design cavities so that, as far as possible, internal support structures are avoided. One way to accomplish this is to design all channels and cavities with a sloping ceiling (45°) as shown in the example below (Figure 19). To achieve good results and "smooth" surfaces the radius on the top should be maximum 0.5mm (on the machines used by Tronrud). Flat ceilings are possible for channels up to 3mm wide, but the surfaces will be rough and result in poor flow through the channel. It may be noted that while often smooth flow properties are desired, turbulent flow can actually be of benefit in certain cases (e.g. the cooling channels of Use Case 2).

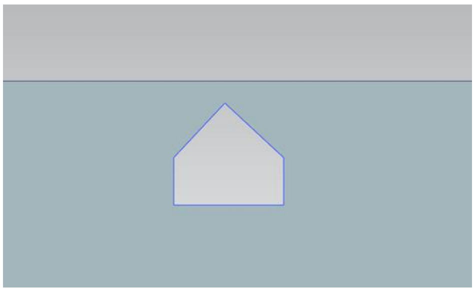

FIGURE 19: SLOPED CEILINGS IN CAVITIES CAN BE USED TO AVOID INTERNAL SUPPORT STRUCTURES

As mentioned above, depending on factors such as orientation, heat dissipation and size of the voids, some support structures may still be required. Support structures that can easily be removed will not form part of the final product and therefore do not need to be included in the design stage. However, support structures that are internal and non-removable should be included in the design. If the process planning of WP3 indicates a need for internal support structures, this information should be communicated back to WP2. There may be a need to re-run the WP2 analysis to ensure that the expected properties are maintained (e.g. that the support structures do not block the flow of the cooling channels). The digital representation of the support structures to be included can be considered to be part of the material part of the design. An alternative modelling method is to manipulate the void/cavity description in order to incorporate them.

5.2 DESIGN METHODS FOR SUBDIVISION VOLUMES

Similar to subdivision surfaces, Bézier patches or NURBS surfaces, the overall shape of subdivision volumes is defined by a mesh of control points, which can be manipulated in order to create the desired design. The requirements on the topology of this control mesh depend on the chosen subdivision algorithm. While some algorithms require strictly tetrahedral or strictly hexahedral meshes for their control points, the volumetric version of the Catmull-Clark subdivision approach presented by Joy et al. [8] can deal with arbitrary polyhedra.

The modelling of voids and internal structures inside the object will be realised in two different ways: either the user designs the internal structures manually by directly defining the position and the shape of the voids via a 3D modelling tool, or the voids are inserted automatically by an algorithm based on geometrical distribution rules and a fixed set of parameters.

5.2.1 Manual placement and shaping of voids

In this approach, the user will directly interact with the 3D model of the object to insert and design the voids in the preferred way. The user will be provided with a desktop application that

offers the required functionality. Every new void will be inserted as a simple control mesh consisting of just one hexahedron. The user will then be able to design the void by adding cells to the control mesh, adding control vertices within existing cells and most importantly move the control vertices into their correct positions in order to get the desired design.

A more advanced version of the proposed 3D modelling tool will offer additional functionality that ensures topological correctness during editing and checks for other constraints like the minimal distance between two neighbouring voids, the minimal space between a void and the outer surface of the object or the total percentage of remaining material.

5.2.2 Automatic distribution of voids

In this approach, the voids are placed automatically within the object based on appropriate geometric distribution rules and a set of starting parameters defined by the user before triggering the distribution algorithm. These parameters might consist of a set of rules proposed for the manual modelling approach, i.e. the minimal distance between two neighbouring voids, the minimal space between a void and the outer surface of the object and the total percentage of remaining material. Additionally, design parameters like the average size of a single void could be envisaged to create internal structures with either very few large voids or many smaller voids. The overall process could be similar to the algorithm presented by Lu et al. [9], who generate an automatic distribution of voids based on a Voronoi distribution inside the object.

5.2.3 Automatic optimisation workflow

Once the initial set of voids has been placed inside the object, either manually by the user (see Section 5.2.1) or automatically (see Section 5.2.2), the geometric configuration can be used for an automatic optimisation.

The results of a simulation of physical properties might be affected by the positioning and size of the internal structures. These design parameters can be varied to iteratively optimise the design of the inner structures until they meet certain properties, such stress or temperature limits. Therefore, the modelling system will provide an interface that allows positioning and dimensioning of voids within the infrastructure.

This interface will be specified considering work in other work packages.

5.3 INTEROPERABILITY OF SUBDIVISION VOLUMES WITH THE TRI-VARIATE (SPLINE) VOLUMES

At some point in the design process, the subdivision-based inner structure has to be combined with or converted into the tri-variate volume representation of the object itself. From a very high level, this can be seen as a Boolean operation of cutting the voids from the object, leaving one single representation that contains the complete volumetric information with both the outer surface as well as the internal voids. In general, there are three possible approaches of realizing interoperability.

5.3.1 Tri-variate approximation of subdivision volumes

With this approach, the voids are integrated into the object before the meshing step. In order to do this, the subdivision volumes have to be converted into the same tri-variate spline volume representation as the object itself. Unfortunately, there is no mathematically correct conversion

between subdivision volumes and tri-variate spline volumes. Therefore, an approximation is required.

There are many algorithms that approximate given geometry with spline curves and surfaces. These approaches can also be applied to volumetric subdivision representations. Since the inside of the subdivision volume will be hollow, those algorithms could be used to approximate the outer surface of the voids with a spline representation. This can then be integrated into the tri-variate model. The choice of which fitting algorithm to use within the CAxMan project will be based on evaluating different alternatives based on computation time, approximation error and number of resulting control points.

The result is a single block-structured tri-variate model that can then be meshed for the simulation.

5.3.2 Separate meshing of the object and the voids with Boolean operation on tet-level

Instead of combining the object and the voids before the meshing step, both could be meshed individually into a tetrahedral representation. This does only work with the traditional finite element approach and cannot be applied to isogeometric analysis. The discretization can then be generated by intersecting the solid object and the voids on tetrahedral level. Compared to approximating a spline based representation from the subdivision volumes, intersection tests of tetrahedra are rather simple to perform. Depending on the mesh accuracy required for the simulation, this intersection can be realized by discarding entire tetrahedra or more complex by calculating cross sections and creating new tetrahedra at the border between the object and the voids. The performance as well as the accuracy of this approach has to be evaluated and compared to the one described in the previous section.

5.3.3 Direct spline parameterization of subdivision volumes

Another option is to actually define the subdivision volumes in the isogeometric parameter domain and use them directly as the trimming volumes or surfaces for the object. This would also allow geometry to be manipulated while keeping the voids within the object. However, this is of course dependent on the parametrisation.

In Section 4.1.1 the requirement for trimmed volumes in the context of isogeometric analysis is stated. The geometric models may become too complex for a pure block structured tri-variate solution. IGATools currently provide basic quadrature schemes that may be useful to handle trimming in analysis; more details can be found in Section 6.1.2. The incorporation of volumetric subdivision voids has many similarities with the handling of Boolean type trimmed volumes; so it makes sense to pursue the same solutions. The boundary of a volumetric subdivision void might preferably be represented or approximated by a number of spline surfaces.

6 REQUIREMENTS: ANALYSIS TOOLS FOR DESIGN

6.1 ISOGEOMETRIC ANALYSIS

6.1.1 Overview IGA

Isogeometric analysis (IGA) is a paradigm for solving Partial Differential Equations (PDE) in which the solution of the equation is approximated by a linear combination of the same basis functions used to represent the domain of the computation, i.e. splines or NURBS. The coefficients of the linear combination are typically computed with a Galerkin procedure, which in practice amounts to the assembly and resolution of a linear system (which is a standard task in linear algebra, with many algorithms and software available). The first work on IGA was published by Hughes, Cottrell and Bazilevs in 2005, see [10], and the interest of the engineering and mathematical communities in IGA has steadily expanded ever since; see [11] for a comprehensive review.

IGA paves the way for significant savings in the design cycle with respect to the classic finite element analysis (FEA) based on triangular/tetrahedral representations of the computational domain: indeed, converting a CAD geometry into a triangular/tetrahedral mesh is a very time-consuming activity, and moreover represents an additional source of error since typically the conversion will be approximate. Note that some non-trivial pre-processing of the CAD description of the geometry could be needed also if the IGA paradigm is adopted, e.g. in order to convert the boundary representation of the volume (commonly adopted by CAD) into a pure three-dimensional representation as discussed earlier, or to describe complex domains in a way more amenable to computations, as in the case of domains with holes that will be discussed in Section 6.1.2. Yet, we believe that even taking into account this pre-processing, IGA might represent a valid alternative to the classic FEM analysis, although the mathematical understanding and the software technology of IGA is not yet at the level of maturity as the FEM counterpart. Another remarkable feature of IGA is that with NURBS basis functions any desired smoothness of shape functions can be achieved in an elementary fashion, providing an effective way of solving problems that require high smoothness, such as plate and shell problems.

The IGATools library [12] developed at IMATI-CNR Pavia will be used for the IGA simulation.

It is a C++14 library designed for the resolution of PDEs in the IGA context, and it consists of a series of classes that represent the typical concepts involved in the definition and solution of PDEs (functional spaces, basis functions, domains, meshes, etc.). It is based on the so-called "Bézier extraction" [16], which means that in principle any kind of splines/NURBS representation can be used for analysis with IGATools, provided that the corresponding Bézier extraction operators are given. The IGATools library will be the building block upon which we will develop:

1. a module for the solution of elastic problems in the linear and non-linear regime (for both use cases);
2. a module for the solution of heat transfer problems (for Use Case 2, without phase change);
3. a module for the shape optimisation, based on the assumption that the topology of the geometry to optimise is fixed during the optimisation phase (for both use cases, see Section 7.1 for more details).

6.1.2 How to handle voids

One difficulty with NURBS-based isogeometric analysis is the treatment of the problems with arbitrary complex topology (for example a rectangular domain with some void regions in its interior). Since tensor product patches are quite inflexible a single NURBS cannot represent entities (surfaces or volumes) with a complex topology without a multi-patch configuration or trimming techniques.

The multi-patch approach consists in the decomposition of the complex geometry in several tensor-product patches plus suitable gluing operators at the patch interfaces, before the analysis procedures. In the computer aided geometric design, patching multiple NURBS to form a complex topology is not easy, because a level of continuity between adjacent patches should be maintained.

Besides this, if the analysis domain has been modelled by employing trimming operations in a CAD system, these trimmed entities (surfaces or volumes) cannot be directly used for analysis. To build the multi-patch configuration, the original model should be divided into several tensor product patches, which means that the original trimmed entities are discarded and new CAD modelling is required, resulting in a very time-consuming procedure.

The trimming technique provides a promising alternative for representing NURBS domains of arbitrary complex topology [13]. Trimmed NURBS surfaces have become one of the most effective and widely used means ranging from CAD/CAM applications to computer graphics. In the CAD world, actually, it is difficult to construct complex surface representation of two or three-dimensional solids without Boolean/feature operations on simpler entities. These operations result in trimmed regions on the surfaces. The main issue here is that, to our knowledge, no commercial CAD system currently supports general trimmed volumes; instead, the volume is represented as the union of trimmed surfaces that define the volume boundaries (Boundary representation). One particular case of trimmed volumes that could be tackled at present with isogeometric analysis is when the volume is obtained as the result of an extrusion or sweeping operation on a trimmed 2D surface. As for CAD, the analysis of general trimmed volumes, resulting from Boolean operations between tri-variate volumes, is not currently covered by IGA.

In CAxMan, the use of a multi-patch configuration or trimming approach will be chosen depending on the complexity of the geometry used for the simulation:

1. for the cases in which the multi-patch is adopted, we will expect to have non-conforming meshes at the patch interfaces, and for the construction of the suitable gluing operators we will use mortar-like techniques [14].
2. for the cases in which the trimming approach is adopted, we must deal with the integration over the trimmed elements; we will investigate the use of composite quadrature schemes similarly to the "Finite Cell Method" approach [15].

6.2 REQUIREMENTS FOR THE NUMERICAL SIMULATION OF THE AM PROCESS

Numerical simulations will be conducted to assess different properties of the manufactured parts. There exist two possibilities to prepare the input data for the numerical simulation of the AM process:

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 support structures used during the AM process. As a further step, the simulation package will perform the slicing of this volume to get a layered domain split 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 as well as the definition of the supporting system is not necessary. The mandatory input data is the actual scanning sequence and the layer thickness set for the AM machine, which is the expected output of WP3.
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 support structure must be available too. The corresponding volumes defining both the part and the support 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 surface) representing the current powder bed level. The volume between two horizontal surfaces 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.

This given, the requirements for the simulation package are the following:

- **CAD geometry** (STEP, IGES format) of component and support structure. Only for option 2.
- **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 for a high fidelity simulation. When the simplified layer-by-layer method is assumed, this information is not necessary.

7 REQUIREMENTS: TOOLS FOR OPTIMISATION

At present the only optimisation loop within the CAxMan use cases is the one performed by STAM in the design process on the balancing mass.

The problem can be solved with the CAD software used by the company: by optimising one of the components of the inertia matrix of the input shaft either the static or the dynamic balance of the gearbox can be reached. The problem is generally solved as a single-objective optimisation, meaning that the dynamic balance is reached and the static unbalance is evaluated afterwards. The constraints of the optimisation are set on the geometry of the balancing mass (i.e. avoidance of interference with other parts, limits in one specific direction, etc.).

The multi-objective optimisation of the inertia characteristics, in order to solve both the static and dynamic problems at the same time, has never been attempted by STAM.

In this regard, it is worth to underline that the shape of the balancing mass is generally also driven by its manufacturability by means of CNC milling: AM may allow more optimal shapes with less material usage.

During the design of a NUGEAR, STAM also optimises the dimension of the gear to the nominal torque of the gearbox. At present, an initial attempt of this value is computed with traditional formulas from mechanical engineering and company know-how (see Section 2.1.1). After this the module of the gear is refined or verified with FEM analyses. Thus, this process is solved with a trial and error approach.

In any case, it should be noted that this issue cannot be considered as a real optimisation problem: since the torque that the gearbox can transfer is cubically proportional to the module of the gear, it is expected that the optimal solution will always be found in the proximity of the problem constraints.

Finally, an extremely interesting optimisation that STAM does not perform to date is that of the tooth shape. In fact, in the majority of gears for power transmission, pure involute profiles are not used and the micro-geometry of the tooth shape is modified so that the contact nominally takes place at a point instead of over a line. This is due to severe malfunctioning of the gears (e.g. edge contact) in case of elastic deformation, manufacturing tolerances and installation errors.

There are several methods to correct the tooth micro-geometry, such as tip relief, end relief, lead crowning and profile crowning. They can be effectively used to minimize the transmission errors, which is the main source of noise and vibration in gears.

In addition, more sophisticated optimisation approaches exist, that allow for:

- Distributing the contact pressure over the face of the tooth, avoiding edge contact;
- Minimising the transmission error;
- Reducing shocks after motion stops and reverse motion;
- Reducing bending stress at the tooth root.

In other terms, these micro-corrections allow maximising the fatigue life of the gear, minimising noise and vibrations, and maximising the transmittable power density.

These methods are generally not employed because their deployment requires the modification of machine motions (during gear manufacturing) and/or of the tools and intensive FEM calculations, so very few gear manufacturers can provide these solutions.

This problem can take advantage of AM and of the possibility to generate free form parts. An optimisation problem must be set up, with related objectives, whose design variables coincide with the optimal values to be given to the micro-corrections.

The micro-geometry (ease-off topography) is generally represented as a polynomial surface (e.g. up to the fourth degree): the polynomial coefficients are the design variables to be determined. The objective functions are: average efficiency loss, maximum contact pressure and transmission error under load. Several programs are available in literature to evaluate the objective functions. The constraints of the problem are given by the need to avoid edge loading: we require that the total load acting outside the allowable contact area (specified for instance in AGMA standards) is zero.

This optimisation problem would be an interesting development for STAM, to improve the performances of the NUGEAR, taking advantage of AM.

7.1 OVERVIEW: OPTIMISATION LOOP

For both use cases, optimisation with respect to parameters related either to the material properties of the considered object or to its geometrical description can be considered; the parameters of interest will be decided in agreement with the industrial partners (Missler, STAM).

We will assume that the optimisation parameters are described by scalar quantities, possibly constrained by lower and upper bounds; the mathematical aspects of this kind of optimisation are nowadays well understood and several algorithms are available to perform this task, see e.g. [17].

More specifically, concerning the material properties of the objects, we will consider either homogeneous materials or graded materials with a relatively easy constitutive law, which can be parameterized with a few scalar values.

As for the geometrical description, we will consider one (or possibly a few) starting configurations of the geometry, modelled by spline/NURBS, and we will perform an optimisation with respect to some suitable parameters describing such geometries. Both the starting configurations and the parameters subject to optimisation will be chosen together with the industrial partners; for instance, we might consider

1. the position of the control points describing the geometry, but fixing a-priori their number;
2. quantities like diameters/heights or other characteristic lengths describing the geometry (e.g. the length of the pipes/the height and width of a cooling chamber/the shape of the teeth of the gear/the scale factor of the gear), but fixing a-priori the topology (e.g., the number of pipes/the shape of a cooling chamber/the number of teeth of the geared wheel).

In such a framework, there is no need for a complete redesign of the domain at each iteration of the optimisation loop. Using a splines/NURBS model of the geometry will grant us the flexibility needed to test several variations of the starting configurations in an effective way. The only requirement is that the splines/NURBS model of the geometry is implemented so that changing the values of these characteristic lengths can be done quickly and in an automated way.

It is however important to remark that the optimisation process could be very computationally demanding, depending on

1. the structure of the function to be optimised (objective function), in particular the presence of local minima and its degree of differentiability with respect to the parameters to be optimised;
2. the number of the parameters to be optimised;
3. the cost of the IGA/FEM solver, which needs to be repeatedly invoked during the optimisation procedure.

In particular, very efficient optimisation methods are available if the derivatives of the objective function can be computed (Gradient method, Newton and Quasi-Newton methods), while non-differentiable objective functions (or those for which computing the derivatives is too complicated) can be tackled with derivative-free methods like the Nelder-Mead simplex method [17] or genetic algorithms [18], which are, however, more computationally demanding. Local minima can be treated with multiple restarts of the optimisation method or with suitably randomized algorithms, e.g. simulated annealing [19].

In general, if the number of parameters is not too large and the IGA/FEM solvers are not too CPU-intensive, it could be possible to use the solver directly within the optimisation procedures mentioned above, i.e. to evaluate the IGA/FEM model at each of the points proposed by the optimisation procedure. Conversely, one should devise a two-step optimisation procedure, based on surrogate models.

Surrogate models are simplified computational models that are able to yield sufficiently accurate approximations of the full model (in this case, the IGA/FEM solver), but are cheaper to evaluate than the full model. Computing such surrogate models, of course, requires solving the full model for some selected values of the optimisation parameters, but often the number of evaluations needed to build the surrogate model is much less than the number of evaluations that are needed by the optimisation procedure. Thus, the overall cost of computing a surrogate model first and then using the surrogate model in the optimisation procedure could be much lower than using directly the full model within the optimisation procedure. Several alternative methods to derive such surrogate models are available in the literature, e.g. Sparse Grids [20], Polynomial Chaos Expansions [21], and Reduced Basis Methods [22] to name a few. A complete discussion and study of the advantages and disadvantages of each of these methods, however, exceeds the aim of the project. If needed, we will choose only one of them based on existing comparative literature and on the expertise available within the members of the project.

8 REQUIREMENTS OVERVIEW

The requirements have been collected and described in detail in this document. In order to give a short overview, the following table briefly lists the requirements. Besides the description, the last column gives an indication if the requirement has an impact on standardisation, i.e., if the findings, experiences or developments will be considered for standardisation in this project.

Requirement title	Requirement description	Impact on standardisation
Simple user interface for block structuring	User interaction may lead to an improved block topology of the tri-variate model. A simple user interface can give a tool for the user to specify some corner points in a block structured model and also modify curves between boundary surfaces of adjacent blocks. Functionality to help identify matching boundaries of volume blocks is necessary for the subsequent isogeometric analysis.	No
General requirements for isogeometric analysis	1. Volumetric representation of the geometry (multi-patch or trimmed) (**impact on standard). 2. Information about the type of material associated to the different parts, the mathematical model to be solved (e.g. elasticity, heat transfer, fluid dynamics, etc.) and the appropriate boundary conditions (prescribed displacements, loads, temperature distribution, etc.).	Yes
Block structure requirements	1. In critical areas, avoid extraordinary points, singularities and block boundaries. 2. The remodelling typically implies an approximation, but the structure needs to allow good accuracy compared to the initial model. 3. The constant parameter curves in the tri-variate model should correspond to flow lines for the desired analysis. 4. The model should have well-shaped blocks and elements (B-spline patches). 5. The number of blocks in the tri-variate models should be kept to a minimum. 6. The blocks must meet in a corner-to-corner configuration, i.e. no T-joints are allowed (**impact on standard).	Yes
3D model requirements	1. The initial STEP model should have a good quality, obeying the tolerance provided in the model, and many small surfaces in the geometry description should be avoided. 2. In the file describing the geometry, matching boundaries of volume blocks must be specified, with connectivity information on each side of the interface (**impact on standard). 3. The regularity (non-singularity, good aspect ratio) of the block parameterization should be guaranteed along the design process. 4. Refinement routines for the block parameterization that preserve mesh compatibility should be provided. 5. Tools for visualization are required to allow for user	Yes

	involvement in the block structuring process and for quality control of the model. 6. GoTools must provide a tool performing Bézier extraction of LR B-spline surfaces and volumes (**impact on standard).	
Optimization requirements	1. Information about the objective function to be optimised and on the constraints to be satisfied by the optimised solution are required. 2. One (or possibly a few) starting configurations of the geometry, and the control points to be moved (which might be specified indirectly, e.g. the user might just require optimisation of a characteristic length like a diameter or a thickness). 3. The material properties subject to optimisation (if any) are required (**possible impact on standard).	Yes
Feedback loops WP3, WP4	There are feedback loops from WP3 and WP4 to WP2 indicating that there might be a need for changing the geometry. We expect this change request to come in the format of points/curves/surfaces that the tri-variate model should adapt to or some modified B-spline coefficients implying that nearby coefficients also will need to be changed in order to maintain a good parameterization of the model. The actual format of this revision request must be specified so the consequences can be taken into consideration at an early stage of the implementation.	Yes
Integrate AM data requirements into STEP	The additive manufacturing process is one of the stages in the production of a product. Data that describes the product and its process related attributes need to flow efficiently into and out of this manufacturing stage. Data exchange is, however, not the only data interoperability related requirement. It will also be possible to collect all product description data into a single and consistent data set, which, thus, will contain all data that were accumulated for that product throughout its lifecycle. STEP/ISO 10303 provides this holistic product data view.	Yes
Use STEP for AM data exchange	Product data, such as, shape, material, analysis results and manufacturing instructions need to be exchanged among design, analysis and manufacturing applications. For applications that are under the control of the consortium such exchange shall use an AP238/242 EXPRESS schema extended by CAxMan and the file format ISO 10303-21.	Yes
Data configuration control by the PLM Server	The entire product development process shall be recorded to become traceable over the lifetime of the product. Such records consist of data and documents that various stakeholders and tools contribute to for different disciplines and lifecycle stages. All released information shall be collected in the CAxMan PLM Server.	Yes
CAD model representation formats	CAD model formats STEP or IGES for the analysis of point clouds from dimensional control are required.	Yes
Direct slicing	In order to preserve the material and geometric	Yes

of the tri-variate model	properties to process planning and subsequent stages, it may be needed to perform slicing directly on the tri-variate model. This may include slicing of LR B-splines and subdivision surfaces, associating correct material distribution from field data.	
Intuitive user interface for manual design and placement of voids and cavities	The CAxMan infrastructure should provide an application that allows interactive design and placement of voids and cavities. It should contain a graphical user interface that provides intuitive 3D modelling functionality to the user.	No
Integration of voids and cavities modelled as subdivision volumes with the original object geometry	After designing the voids and cavities for a given geometry, they have to be integrated into the original object geometry for further processing. Therefore, the CAxMan infrastructure must provide a functionality that allows this integration, either by transforming the volumetric subdivision representation of these voids and cavities into a matching tri-variate parameterization or by separate meshing and combination of the resulting discrete representation.	No
Boundary conditions for design of voids and cavities	Since the resulting object should be manufacturable, a set of boundary conditions for the design of voids and cavities must be defined. Possible conditions are the minimal distance between two neighbouring voids, the minimal space between a void and the outer surface of the object and the total percentage of remaining material. These limitations have to be respected when modelling voids and cavities, either manually by the user or automatically by an optimization algorithm.	No
Integration of non-removable support structures	Support structures that cannot be removed (e.g., because they make up internal structures) should be included in the design so that the analysis can be reapplied in order to check for changes in the functional properties of the object.	No
Powder removal channels	For powder bed AM, powder removal channels should be included for all closed voids.	No
Meshing tool	A meshing tool is required to generate the mesh of each layer in between two consecutive horizontal planes representing the powder bed level. Minimum one element through the layer thickness.	No
Scanning sequence (CLI file in ASCII format)	A CLI file in ASCII format is required for a high fidelity simulation. When the simplified layer-by-layer method is assumed, this information is not necessary.	No

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