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# A method for design for additive manufacturing rules formulation through Spatio-temporal process discretization

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**Abstract**

Additive Manufacturing (AM) has many advantages, but the lack of access to the knowledge associated with it minimises its development in industry. The design phase is crucial for the success of AM, a challenge for Design for Additive Manufacturing (DfAM) methods is therefore to facilitate the access and manipulation of this knowledge. This transfer of knowledge can be achieved by formalising rules at all scales, and communicating them to the designer at the appropriate phase. It is hence necessary to find a way to formalise information in time, space and space-time dimensions since AM is a process that places material in space and layer by layer. The concept of mereotopology is used to study the relationships of connection and interaction between parts, wholes and boundaries, and may be a suitable resource to study DfAM along these three dimensions. The aim of this paper will therefore be to present a method for searching and formulating design guidelines based on a discretisation of the process enabled by the concept of mereotopology. This method consists in the decomposition of a 3D model into features between which spatial, temporal and spatio-temporal interactions are studied. Simultaneously, the analysis of manufactured defects on a printed version of the model allows to link manufacturing defects with a configuration of spatial and temporal elements. Once the defects and configurations have been linked, rules are formulated and then validated or invalidated according to their recurrence on different models printed with the same process and material. This method could be integrated in industry to take advantage of manufacturing defects in order to add data to the statistical study.



*Keywords:* Additive Manufacturing; Design for Additive Manufacturing; Design guidelines; Mereotopology; Detailed design

## 1. Introduction

Several factors are still holding back the development of Additive Manufacturing (AM) in the industry. One of them is that the restrictions induced and the opportunities offered by the AM processes are not always known to designers, who might therefore favour traditional methods and miss out on innovations that could have been made possible with AM. One way to promote its development is to facilitate access to AM-related knowledge [19]. Information must be provided to the designer throughout detailed design of the product, taking into account constraints at all scales. Guidelines for AM have been developed on a macroscale, i.e. considering the object as a whole, in its shape, orientation and location [6][15]. Others have been developed at the scale of a layer, which is called the mesoscale [16], and finally at the scale of the micro-structure, which is considered as the microscale [9]. The development of benchmark parts provides quantitative information about the influence of various parameters on the printing quality of characteristic geometrical features [23]. However, different phenomena occur during the printing process depending on the spatial organisation and the chronology in which the different features are printed. The objective of this paper will therefore be to present a method to search for and formulate design rules at the mesoscale in order to provide designers with AM constraint information during detailed design.

A state of the art of methods, guidelines and tools for AM, as well as on mereotopology as a means of formalisation is first presented. The discretization of the AM process in time, space and space-time is then introduced to obtain a way to formulate detailed design rules. Finally, a research and formalisation method is defined. It is illustrated and discussed through a case study.

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## 2. Literature review

### 2.1. Design, guidelines and tools for AM

The notion of Design for X (DfX) refers to guiding the design of a product according to either a stage in its life cycle, or a given constraint [12]. DfAM methods consist in optimising the design through the integration of AM-related knowledge. The methods can be applied at the beginning of the design process or afterwards in order to assess if the solutions found are in line with the initial objectives [13].

A popular DfAM approach is to start from defining the functional surfaces and to design the rest of the part by making use of the advantages of AM [20]. The emergence of topological optimisation (TO) and the use of lattice structures have allowed to make a lot of progress in optimising the design of parts manufactured in AM. For example, Boyard et al. [2] propose a method that starts from a graph of function from which the functional surfaces are deduced to create a preliminary solid, which is then refined by using TO. Moreover, it has been pointed out that the combination of lattice structures and TO allows the optimal solution to minimise a part's weight [22].

Computation-based DfAM methods are therefore widely used for optimisation purposes. However, few researches are conducted on the integration of manufacturability constraints in this type of methods. To optimise the design of a product, it is necessary to take into account the constraints related to AM as early as possible in the design process. It has been shown that the best way to achieve this is to combine computational and knowledge-based methods [21]. It is therefore necessary to develop guidelines for design for AM.

Rules of this type have been established, often in the form of guidance on the limiting sizes and orientations of certain geometric features, as proposed by Thomas et al. [18] for the Selective Laser Melting (SLM) process. In some cases the objective of the designer may be to verify the manufacturability of a product in AM. Manufacturability analysis tools are developed for this purpose, in some cases to choose the global orientation of a part in order to obtain the best result [15], in others to ensure that the printing of an element will proceed properly. This is for example the purpose of the "Will it print" tool developed by Budinoff et al. [3] which analyses features and highlights problematic geometries, such as walls which are too thin to be printed according to mathematical rules that have been formulated.

However, these methods apply to isolated features, but in practice a single part is composed of several geometric shapes that can interact with each other. These features can cause problems during printing depending on their position within the part. Changes in geometry take place when passing from one layer to the next. Depending on where a feature is located, as well as when it is built compared to the others, different physical phenomena can take place locally. It is therefore interesting to formulate guidelines that take into account the features and their interactions, at the transitory scale between successive printing layers, which can be called the mesoscale.

### 2.2. Mereotopology

AM consists of the deposition of material in layers, built up one after the other, it is therefore a process that can be discretised in time, space and space-time. Such a discretisation can allow to locate and formulate some mesoscale design guidelines, by using for example the concept of mereotopology.

Mereotopology is a philosophical theory that arose from the combination of mereology and topology. Mereology was first introduced by S. Lesniewski and refers to the study of the relations between parts and wholes [14]. Topology is a theory based on the notion of connectedness, and can be described as a study of spatial relations [4]. A definition of mereotopology could therefore be the study of the relations of connectedness and interactions between parts, wholes and boundaries [17].

The physical or temporal entities that are studied and between which interactions take place are called regions. A Time Region (TR) will therefore be a time interval or a moment in time [8]. Regarding the spatial regions, their nature will depend on the field of study. The relationships between regions can be described by using primitives that can be spatial, temporal or spatio-temporal (ST). The fields of application of mereotopology are numerous, ranging from geography to artificial intelligence [7].

In the case of spatial interactions, Smith [17] has formulated a set of primitives with the format x**I**y, x and y being the spatial regions we want to describe, and I the symbol of the primitive (Fig.1(a)). For example (x**P**y) means that x is part of y. x**T**y means that x is tangential to y, that is to say that the spatial regions x and y have one point in common but are not overlapping.

Regarding temporal interactions, Allen [1] has defined several primitives that are used in a similar way (Fig.1(b)). For instance, the designation x=y means that the time regions x and y are starting simultaneously and ending at the same time.

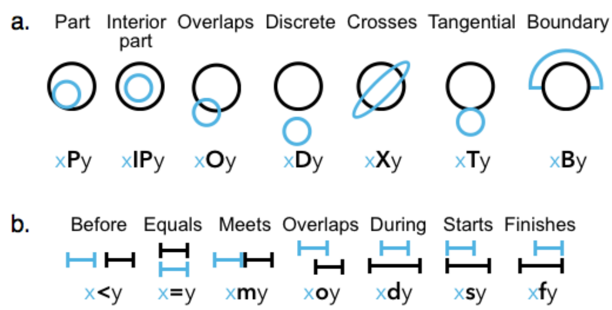


Fig. 1. (a) Smith's primitives [17]; (b) Allen's primitives [1]

In the field of AM, Khan and Kim [11] have used spatio-temporal mereotopology to describe the different stages of an AM assembly, i.e. the evolution of the surfaces that interact during the folding process of an element manufactured in AM. However there is no current record of using spatiotemporal mereotopology to describe the additive manufacturing process in itself.

## 3. Discretization of AM processes

### 3.1. Spatial and temporal discretization

Smith's and Allen's primitives are relevant to describe the spatial and temporal interactions occurring during the manufacturing process and have therefore been used in this study. First, isolation of regions based on slicing is required. On each layer, several spatial regions can be observed, and can be classified into 3 types:

- The material that is used to build the final product and which is not intended to be removed will be referred as *matter* (M) for the rest of the study.
- The support material is the matter which is added in addition to the product in order to support surfaces which are too far from any point of attachment to be built otherwise. Any material used for manufacturing purposes but which is not part of the final part will be called *support* (S) hereafter.
- In opposition to these two categories, a third type of element is defined, *void* (⊘), which corresponds to an absence of matter and support at a given spatial area.

Thus, Smith's primitives allow the spatial description of interactions between elements of different types or of the same type within a layer. Besides, it is considered that each spatial region perdures in time. The perdurantist approach implies that each region is considered as a 4-dimensional object consisting of all its representations in time [10]. In other words, if the geometry of a region changes over time, it is still considered as the same entity.

The same entity can thus be present on several layers, but changing slightly from one layer to the next. Considering the fabrication of a layer as a unitary temporal region, the interval of layers on which a spatial entity is present will constitute a temporal region. Thus, Allen's primitives enables the temporal description of the interactions between the builds of different spatial features.

However, the spatial evolution of the geometry in time cannot be characterised with the existing primitives, so it is necessary to develop a spatio-temporal discretization in order to study the evolution of spatial regions through time.

### 3.2. Fundamental ST primitives

In order to determine a set of ST primitives, a layer-by-layer analysis was performed on several 3D models. For each model, three orientations were chosen and the printing process was simulated with a track thickness of 1mm. By observing the evolution of every spatial regions from one layer to the following, the list of ST primitives described in Fig.2 has been developed.

The primitives are represented by two bold letters and are framed by the two elements interacting. x and y are distinct spatial regions, and z represents the entirety of either the matter (M) or the support (S) present on the layer. The description is divided into a succession of time regions noted TR, which is equivalent in this case to the building of one layer. Within each interval, Smith's primitives are used to establish a spatial description of the interaction between the elements. In addition, fundamental operators of mereotopology are used for these descriptions [5]. In this paper, the symbols ∧ and ∨ respectively stand for "logical conjunction" and "logical disjunction", i. e. "and" and "or".

| Spatio-temporal primitives | | Mereotopological descriptions |
|---|---|---|
| x**Ap**z | x Appears in z | $(x\mathbf{P}\emptyset)_{TR1} \wedge (x\mathbf{P}z)_{TR2}$ |
| x**Di**z | x Disappears from z | $(x\mathbf{P}z)_{TR1} \wedge (x\mathbf{P}\emptyset)_{TR2}$ |
| x**Me**y | x Merges with y | $((x\mathbf{P}z) \wedge (y\mathbf{P}z) \wedge (x\mathbf{D}y))_{TR1} \wedge (x\mathbf{T}y)_{TR2} \wedge (x\mathbf{X}y)_{TR3}$ |
| x**Se**y | x Separates from y | $(x\mathbf{X}y)_{TR1} \wedge (x\mathbf{T}y)_{TR2} \wedge ((x\mathbf{P}z) \wedge (y\mathbf{P}z) \wedge (x\mathbf{D}y))_{TR3}$ |
| x**Ai**z | x Area increases in z | $(x\mathbf{P}z)_{TR1} \wedge ((x)_{TR1}\, \mathbf{P}(x)_{TR2})_{TR2}$ |
| x**Ad**z | x Area decreases in z | $(x\mathbf{P}z)_{TR1} \wedge ((x)_{TR2}\, \mathbf{P}(x)_{TR1})_{TR2}$ |
| x**Ac**z | x Area is constant in z | $(x\mathbf{P}z)_{TR1} \wedge (x\mathbf{P}z)_{TR2}$ |
| x**Cg**z | x Changes geometry in z | $(x\mathbf{P}z)_{TR1} \wedge ((x)_{TR1}\, \mathbf{X}y)_{TR2}$ |
| x**Mo**z | x Moves within z | $(x\mathbf{P}z)_{TR1} \wedge ((x)_{TR1}\, \mathbf{X}(x)_{TR2})_{TR2}$ |

Fig. 2. Fundamental ST primitives

For example for the x**Me**y primitive, x and y are both either matter or support and are distant from each other $(((x\mathbf{P}z) \wedge (y\mathbf{P}z) \wedge (x\mathbf{D}y))_{Tr1})$. During a second interval, corresponding to another layer, x and y become tangent $((x\mathbf{T}y)_{Tr2})$, and finally they end up crosses in the third time interval $((x\mathbf{X}y)_{Tr3})$.

As a result, it becomes possible to describe the spatio-temporal evolution of spatial regions when progressing from one layer to the next.

### 3.3. Common ST primitives

The set of ST primitives mentioned above enables the description of ST interactions between one layer and the following. However, to determine rules at the multi-layer scale, it is necessary to have a little more distance and to observe the evolution of geometry over a wider layer interval.

Some geometric shapes within a single object can be problematic during printing. Benchmarks such as the one proposed by Vorkapic et al. [23] allow a number of parameters to be tested by offering a variety of shapes found in printed models. Based on these shapes and personal experience, a set of features (Fig. 3) has been developed, and described spatio-temporally using the previously defined primitives. This new set is referred to as common ST primitives, and it provides a means of description at different scales. At the macroscale they can be used to describe simple geometric elements. At the mesoscale, they describe portions of geometric elements and thus allow the description of complex geometric shapes discretized into smaller simple features.

When considering the extrusion for example, it can be either orthogonal or swept. In the first case, this means that the geometry will have the same shape from one layer to the next, either maintaining its area (x**Ac**z), increasing it (x**Ai**z) or decreasing it (x**Ad**z). The use of this feature consequently requires to specify the type of surface evolution involved.

Thus, the study of benchmark artefacts specific to AM as well as a layer-by-layer study of 3D models have enabled the es-

| Common ST primitives | | Mereotopological descriptions |
|---|---|---|
| Extrusion | Orthogonal | $(x\mathbf{Acz} \vee x\mathbf{Aiz} \vee x\mathbf{Adz})_{TR1}$ |
| | Swept | $(x\mathbf{Moz} \vee x\mathbf{Cgz})_{TR1}$ |
| Variable section volume | | $(x\mathbf{Cgz})_{TR1}$ |
| Hollow volume | With support | $(x\mathbf{IPM})_{TR1} \wedge (S\mathbf{IP}x)_{TR2} \wedge (x\mathbf{IPM})_{TR3}$ |
| | Without support | $(x\mathbf{IPM})_{TR1} \wedge (\emptyset\mathbf{IP}x)_{TR2} \wedge (x\mathbf{IPM})_{TR3}$ |
| Shell | Right side up | $(x\mathbf{IPM} \wedge (s\mathbf{IP}x \vee \emptyset\mathbf{IP}x))_{TR1} \wedge (x\mathbf{IPM})_{TR2}$ |
| | Upside down | $(x\mathbf{IPM})_{TR1} \wedge (x\mathbf{IPM} \wedge (s\mathbf{IP}x \vee \emptyset\mathbf{IP}x))_{TR2}$ |
| Horizontal hole | With support | $(x\mathbf{IPM} \wedge y\mathbf{IP}x)_{TR1} \wedge (x\mathbf{X}y)_{TR2} \wedge (x\mathbf{T}y)_{TR3} \wedge (s\mathbf{T}x \wedge s\mathbf{T}y \wedge x\mathbf{D}y)_{TR4} \wedge (x\mathbf{T}y)_{TR5} \wedge (x\mathbf{X}y)_{TR6} \wedge (x\mathbf{IPM} \wedge y\mathbf{IP}x)_{TR7}$ |
| | Without support | $(x\mathbf{IPM})_{TR1} \wedge (x\mathbf{Se}y)_{TR2} \wedge (x\mathbf{Me}y)_{TR3}$ |
| Vertical hole | | $(x\mathbf{IPM} \wedge y\mathbf{IP}\emptyset \wedge \emptyset\mathbf{IP}x)_{TR1}$ |
| Overhang surface | With support | $(x\mathbf{IPM} \wedge y\mathbf{IPS})_{TR1} \wedge (y\mathbf{IPM} \wedge y\mathbf{X}x)_{TR2}$ |
| | Without support | $(x\mathbf{IPM} \wedge y\mathbf{IP}\emptyset)_{TR1} \wedge (y\mathbf{IPM} \wedge y\mathbf{X}x)_{TR2}$ |
| Bridge | With support | $(x\mathbf{TS} \wedge y\mathbf{TS} \wedge x\mathbf{Me}y)_{TR1}$ |
| | Without support | $(x\mathbf{T}\emptyset \wedge y\mathbf{T}\emptyset \wedge x\mathbf{Me}y)_{TR1}$ |
| Rib | | $(x\mathbf{IPM})_{TR1} \wedge (y\mathbf{IP}(x)_{TR1} \wedge y\mathbf{T}\emptyset)_{TR2}$ |
| Slot | | $(x\mathbf{Se})_{TR1}$ |

Fig. 3. Common ST primitives

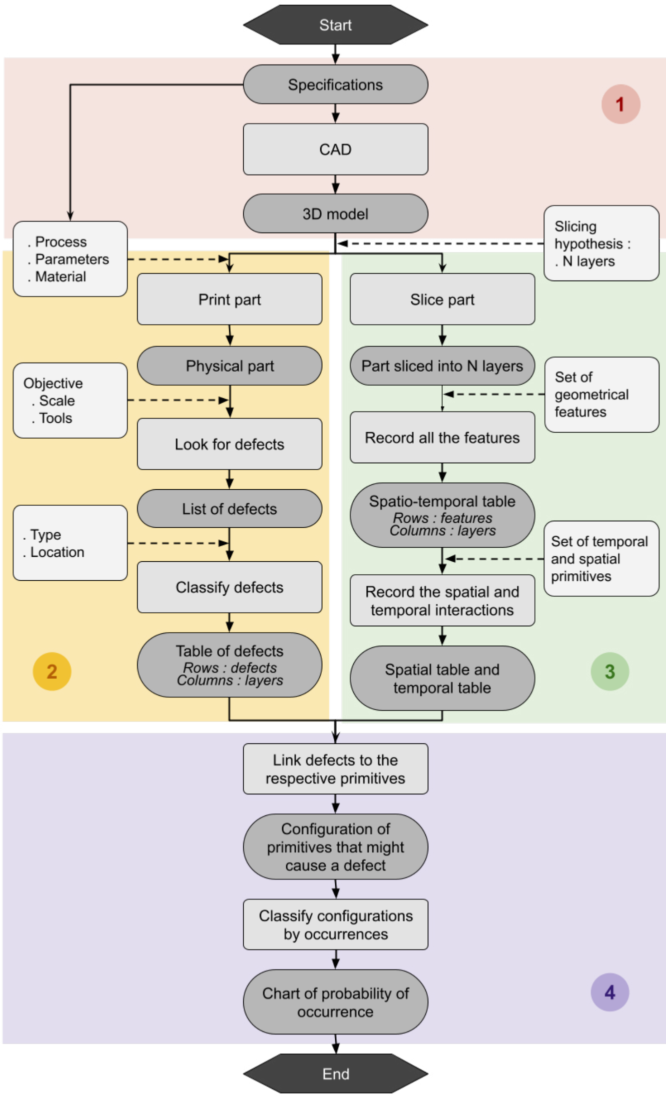


Fig. 4. Protocol for design rules formulation

tablishment of a spatio-temporal discretisation of the AM process. This discretisation is based on geometries that are independent of the material or process used. This model is therefore applicable to any layer-by-layer manufacturing processes.

## 4. Method for design guidelines formalisation

### 4.1. Research protocol

In order to create and formalise some rules for AM design, a protocol using the discretization above mentioned has been set up. This method can be broken down into 4 parts. The first step (1 on Fig.4) is to choose a part and to design it according to the specifications. The process and material used must be specified so that the resulting rules can be classified according to the right application. The 3D model created is then used for steps 2 and 3 which can be carried out simultaneously. This model is imported in a slicer and depending on the part's size, a number of layers "N" is determined. This number is not related to the printing parameters and will simply be used as a temporal unit of measurement for the spatio-temporal study. N should be high enough to allow a certain degree of precision while avoiding being too large so that the discretization is not too complex.

Step 2 is the defects analysis. The 3D model is printed with the parameters, process and material stated in the specifications. Then, the objective of the study must be defined. Depending on the type of rules that are going to be formulated, the scale and the tools used for the analysis will be different. For microscopic defects, tomography imaging can be used for instance. Once this is done, all the defects present on the physical model are listed and classified depending on their type and location. A table is then built, with N columns and one row per defect. Thus, the layer interval on which the defect is present is highlighted.

The mereotopological analysis (step 3) is carried out by observing the 3D model slice by slice. The feature recognition at the mesoscale is done layer by layer and varies depending on the slicing direction. It is therefore crucial to respect the direction in which the part was printed. Every geometrical features from the set defined previously are recognised and listed in what will be referred to as the ST table (Fig. 5 (a)). The columns of this table are the N layers defined during step 1. This table is then declined into a spatial interactions table (Fig. 5 (b)) and a temporal interactions table (Fig. 5 (c)). On the first one, horizontal arrows are placed over the ST table to indicate the time intervals during which each interaction takes place. On the second one, vertical arrows indicate the primitives linking the features with each others.

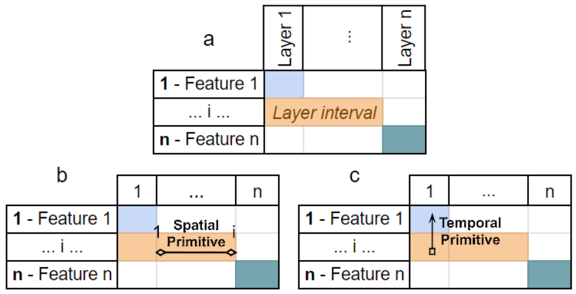


Fig. 5. (a) Spatio-temporal table; (b) Spatial table; (c) Temporal table

The last step is the rules formulation (4 on Fig. 4). The defects, spatial and temporal tables are compared in order to highlight the configurations of primitives that may have caused the defects. This method is based on an evolution of features from one layer to the next, so defects are not always linked to the precise location where it is detected. The spatio-temporal study allowed by mereotopology enables not only to link a defect to the feature on which it is spatially located, but also to the succession of features that precedes it. When the process is repeated on a certain amount of models, the configurations of primitives and defects that tend to appear a lot of times will be considered as general rules. Part quality assessment is used in industry worldwide, the defect analysis phase could thus be associated to 3D model features analyses in order to generate rules. Configurations exceeding a certain number of occurrences would be listed and considered as general rules. These rules, in addition to the guidelines that can be found in literature, can then be implemented in a tool as visual warnings. This tool will transmit the appropriate information to the designer according to his current geometry so that he can identify the problematic areas throughout the detailed design.

## 4.2. Case study

A case study has been carried out on the Benchy (fig. 6 (a)) to illustrate the method. The Benchy is a 3D model designed specifically to test the printers' parameters, hence presenting a huge diversity of shapes and surfaces which can cause problems when printed.

The model has been sliced with a layer thickness of 1mm, thus creating 48 layers (d). By isolating each layer and comparing it to the ones following it, a total of 12 features were noted (e). As the part is symmetrical, the features are only noted once to simplify the study. All the features were sorted in order of construction, starting with the hull and ending with the chimney. By recording the construction interval of each of them, the basis for the spatial (f) and temporal (g) interaction tables was created.

For example, the benchy cabin is a shell whose construction extends from layer 10 to layer 38. In the first table (f) all spatial interactions between features are represented by two-way horizontal arrows with labels corresponding to the interaction. For example the benchy's hold, which is feature 4, is tangent to the cabin, feature 5, from layer 10 to layer 16. A horizontal arrow

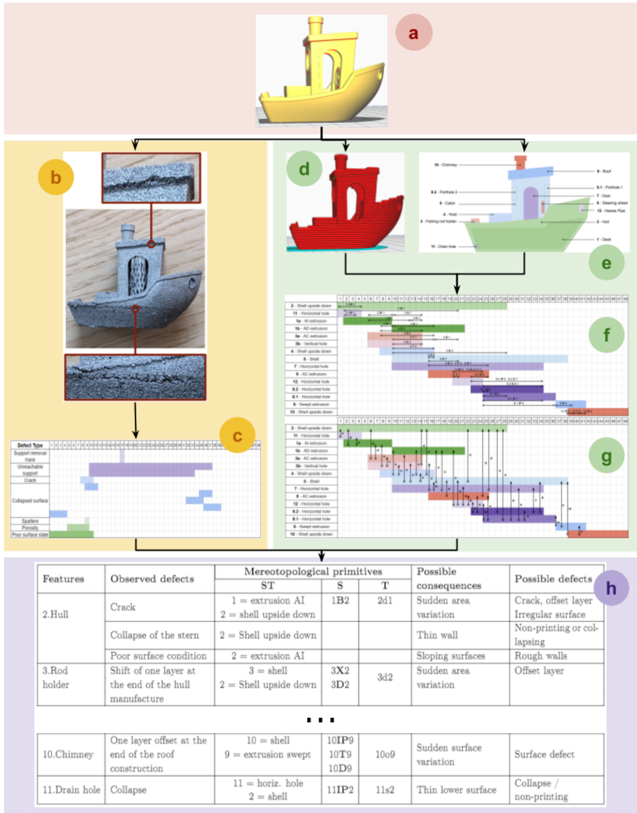


Fig. 6. Rules formulation protocol applied to the Benchy

therefore extends between column 10 and 16 with the notation 4**T**5 (fig. 7).

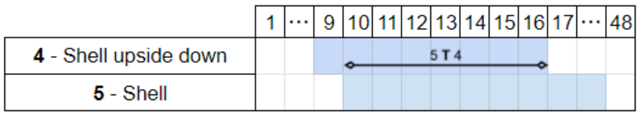


Fig. 7. Extract of the spatial table from the Benchy study

The second table (g) records the temporal interactions between the features, which are represented by single-way vertical arrows labelled with the primitive linking the two features. For instance the manufacturing of the cabin and the doors start at the same time, but the doors are finished first. Thus, an arrow starts on the row corresponding to the cabin and ends on the row of the doors with the label **s** (fig. 8).

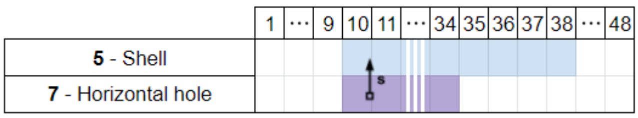


Fig. 8. Extract of the temporal table from the Benchy study

Simultaneously with this mereotopological study, the benchy was manufactured in LPBF with a cobalt-chromium alloy. For the purpose of this paper and its understanding, the defects that were visible to the naked eye have been pictured (b). The 11 defects that were found are classified according to whether they are due to the presence of support (either support removal trace or unreachable support), a surface problem (either spatters or a poor surface state), or some deeper defects (cracks, porosity or collapsed surfaces). In table (c), the layers corresponding to the location of each defect are coloured, and the corresponding features are specified.

Finally, the defects are correlated with the spatial and temporal interactions of the features on which they are located, or simply with one feature. On table (h), the resulting rules are formulated. For example on fig. 9, the rule associated with the crack shown in illustration (b) is that if an upside down shell (Feature 2) is a **boundary** of an area increased extrusion (Feature 1) and that this extrusion is built **during** the building of that shell, the two elements are in contact until the end of the manufacturing of the extrusion, and once its manufacturing is finished, there is only one shell element left, which has a much smaller section. This configuration could therefore cause a sudden area variation that could result in a local heat variation and thus a crack forming.

| Mereotopological primitives | | | Possible consequences | Possible defects |
|---|---|---|---|---|
| ST | S | T | | |
| 1 : extrusion Ai<br>2 : shell upside down Ai | 1**B**2 | 2**d**1 | Sudden area variation | Crack |

Fig. 9. Example of a rule formulated from the Benchy study

The rules stated here are specific to the benchy, and in particular to the one made with LPBF in cobalt-chrome. Repeating this process on other benchys might show different defects and therefore add other specific rules. In order for these specific rules to become general rules, the process must be repeated on other models in order to define which ones are relevant and recurrent, thus establishing a more general set of design guidelines.

## 5. Conclusion

After reviewing DfAM and mereotopolgy literature, a spatial and temporal discretisation was presented. It enabled the definition of primitives adapted to AM, which led to the development and formalisation of a set of spatio-temporal primitives. A method for deducing rules based on mereotopological configurations was shown by using these primitives to decompose different 3D models and by confronting them with common manufacturing defects. This method, which is adaptable to different processes and scales, enables first to formulate rules specific to a given model, and then by applying it to a large number of cases, allows to select rules that can be generalised and thus applicable to any model.

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