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# Applying TRIZ in Design for Additive Manufacturing to Solve Design Contradictions at Multilevel

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**Abstract.** This article proposes a design framework for additive manufacturing (AM) to solve contradictory design problems. Different structural features are selected within different levels of detail (e.g., cellular structures, infill, porosity) to realize the conflicting requirements and properly combined within the structure of the product.
To do this a multilevel interpretation and classification of the options present in a commercial software of Design for AM was provided. Then, criteria to combine the different structural features within the structure of the product were proposed, starting from some principles of the TRIZ (i.e., Russian acronym for "Theory of Inventive Problem Solving") method. The method was applied to design a dental prosthesis and the results, obtained by testing a simplified plastic sample were analyzed. The contradictory problem deals with the realization of both the mechanical resistance, during the chewing, and the thermal resistance to prevent the thermal dilatation during the workpiece finishing operations on machine tools. The sample designed with the proposed method exhibited better performances in both the requirements compared to another sample, made with a microstructure chosen in a completely random way.

**Keywords:** Design for Additive Manufacturing, Multilevel design, Hierarchical complexity, TRIZ
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## 1 INTRODUCTION AND LITERATURE BACKGROUND

One of the clearest advantages of AM is the possibility of designing at different levels of detail, taking into consideration a wide range of structural features (e.g., shape, internal structure, such as lattice, infilling, etc.) by enlarging the solution space. In this way, AM can offer the designer more chances to resolve design contradictions, or those design problems where two requirements are seen as contradicting each other by a designer, depending on her/his experience and creativity [27].

One of the best-known supporting approaches to solve design contradictions is the TRIZ method [1], acting both on reformulation and resolution of the contradiction. During the reformulation, the Control parameter is identified. It is a structural parameter of the product which, designed in one way (Condition 1) allows to realize a requirement and designed in another way (Condition 2), realizes the other. While, during the resolution, a structural configuration in which the two Conditions of the Control parameter are combined in a certain manner within the structure to ensure the fulfilment of both the requirements.

However, the TRIZ approach to solve a contradiction is seen in practice as not very pragmatic, too abstract and difficult to contextualize (e.g. [30]), also in the context of Design for AM. For this reason, some improvements have been proposed in the literature. [20] and [26] introduced some TRIZ and axiomatic design principles in order to make the designer think at different levels of detail, in solving contradictions, to grasp and exploit the complexity and capacities of Design for AM (e.g., topology optimization, infilling, multi-materials, microstructure variation). While the approach of [4] is much more complete in formalizing the design logic on multiple levels of detail to resolve contradictions, without formalizing them as rigorously as in the TRIZ method. It explains how the structure of a piece can be morphologically optimized in each level of detail, finding constraints and forces from higher levels using the topology. However, the link with AM is only hinted at, without dwelling on its structural peculiarities. In essence, these approaches have at least two main limitations. The contradictions are modelled too abstractly to allow the designer to identify the most strategic solutions within the AM, especially if she/he is not a TRIZ expert. The search for solutions to contradictions does not consider all the features and structural limits of the pieces made of AM, which are defined at different levels of detail (e.g. lattice, infilling, microstructure variation, shape of the dust).

Different FEM tools, e.g., Ansys and Abacus enable users to conduct efficient designs with contradictory requirements in design for AM, by properly setting the boundary conditions. However, for several years these tools have been considered not suited for supporting the designers in the conceptual design phase, since they lack a link between this latter and the detailed design activities, although this link is a key to enable companies to be competitive by proposing innovative products [5]. Designers who use such tools have a wide range of design options to solve contradictory design problems, but especially novice designers have little awareness of the real problem to be solved and how to use the tools in this regard. This is because finite elements (FE) tools require specific information, while problem solving is based in big amounts of data that must be modelled, filtered and translated in a more operational way to be then inserted into the FE tools to properly set the boundary conditions [3]. For this purpose, several attempts to integrate FE tools and approaches to model the initial problem have already been proposed in the literature, although limited to very specific applications (e.g. [21], [25]).

This paper proposes a Design for AM framework that supports the resolution of contradictions in design, based on a contextualization of the theoretical approach of the TRIZ method to formalize and resolve a contradiction trough AM. The proposed approach allows to identify the structural features to be used to achieve the contradicting requirements and in their appropriate combination in the structure of the piece made in AM. This contextualization, and in particular the definition of the structural features and the mechanisms of their structural combination, were obtained by analysing several emblematic examples of pieces made in AM that resolve contradictions, taken from the literature. Their analysis was carried out by the authors by analogy with the ontology and theoretical approach of the TRIZ method.

This approach does not replace the traditional FE tools, which already propose design options to solve contradictory problems, by setting the boundaries on purpose, but provides a general interpretative key on how to select and implement them in the product structure in a more conscious way. This is possible thanks to the modelling of the initial problem, in order to support above all less experienced designers. In particular, compared to other Design for AM frameworks that support the resolution of contradictions in design, the one proposed is more pragmatic and is especially dedicated to designers who are less familiar with the TRIZ method's approach to solve contradictions. This is because this contextualization within the AM has been carried out in a complete manner in every part of this approach and considering the structural characteristics of the AM on a broad spectrum of different levels of detail.

## 2 PROPOSAL

The proposed method is a contextualization of the TRIZ approach for formulating and solving a contradiction within the AM. The knowledge base for this activity was collected from completely manual analysis of the scientific literature about AM. At first the search query "Additive manufacturing" was used in the Google Scholar database and the papers obtained describing the realization of two requirements using the AM were considered. Then, among them, the authors identified the control parameter and the separation principles that were used, based on their experience in TRIZ. A total of 18 papers were analysed.

Table 1 reports the analysed articles, classified according to the two contradicting requirements that have been realized with the solution implemented in them.

| *Contradicting requirements* | *Considered papers* |
|---|---|
| MS vs lightness | [7], [33], [31], [5], [34], [14], [17], [36], [15] |
| MS in direction 1 vs MS in direction 2 | [17], [35] |
| MS vs thermal insulation | [32], [18], [16] |
| MS vs acoustic insulation | [37], [28], [22], [29] |
| MS vs lightness | [7], [33], [31], [5], [34], [14], [17], [36], [15] |

**Table 1**: Considered papers classified according to the contradicting requirements (where MS = mechanical strength).

The method that has been extrapolated in this way has been divided into the following three steps:

- STEP 1 - Identifying the contradicting requirements, by modelling the initial contradictory problem;
- STEP 2 - Identifying the structural features at different levels of detail, which are used to implement the requirements within the structure of the product.
- STEP 3 – Implementing the structural features in the product structure, by combining them through the TRIZ principles of separation, so as to allow the product to fulfil both requirements, by solving the contradiction.

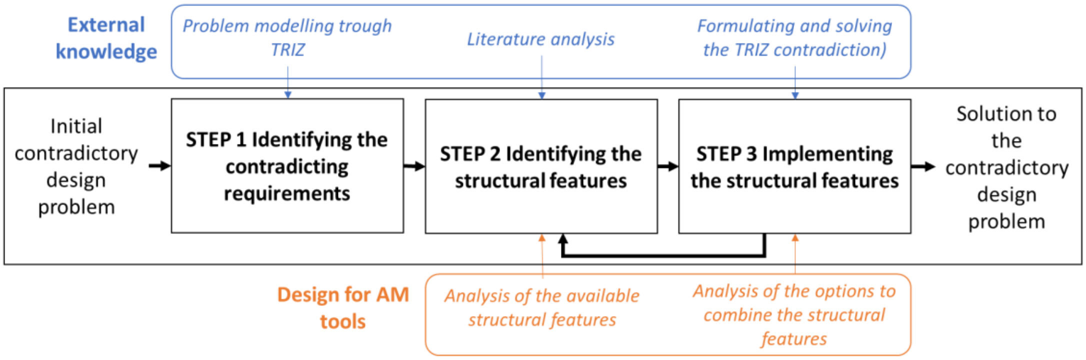


**Figure 1**: A schematic representation of the proposed approach.

Through this schematization (see Fig. 1) it can be seen how the different steps of the proposed method have been defined with the aim of combining external theoretical knowledge of a methodological type (deriving from the TRIZ method) and of a practical type (deriving from the solutions present in the scientific literature) with the structural features and their combination modes, available in a Design for AM tool (e.g., FE tools). This is the main difference of the proposed approach compared to the immediate use of Design for AM tools. The constitutive steps of the proposed method are explained in detail below.

## 2.1 Identifying the Contradicting Requirements

The first step of the proposed method consists in identifying the two requirements that the piece made by AM must guarantee, e.g., mechanical strength and lightness or thermal insulation and acoustic conduction. These two requirements are in contradiction if, once all the initial product requirements have been set, the realization of the first involves the non-realization of the second and possibly other requirements and boundary conditions and vice versa. This procedure for identifying the contradicting requirements was widely supported by researchers belonging to the TRIZ community, proposing various formalizations resulting for example from the integration of the TRIZ method with more structured methods of managing requirements such as Quality Function Deployment (e.g. [12]).

## 2.2 Identifying the Structural Features

In this case, the structures that can achieve the two requirements are defined. The peculiarity of AM is to allow the design within different levels of detail (i.e., piece, internal structure, infilling, wire/powders, material). Each contradictory requirement can therefore be realized by designing a structure made by AM, which exploits the structural features of a given level of detail, although structural features defined within different levels of detail can be used to implement the same contradictory requirement. The choice between the alternative solutions defined at different levels of detail is up to the designer, on the basis of different considerations, such as the mass and the energy consumed by the machinery.

The most common example in Design for AM concerns the reduction of mass. It can be obtained at the macro-level through morphological optimization, at a lower level of detail through the optimization of the lattice, at an even lower level through the optimization of the infilling and at the level of the constituent material, exploiting its porosity. An example related to the realization of another requirement is the patent [23]. In this case, to design the surface roughness of the hip prostheses made of AM, the constituent titanium powders were made by laser pyrolysis in order to obtain a better quality. Consequently, the prosthesis with a better surface roughness, obtained with the AM laser, can reduce the welding time to the bone by up to 40%, according to what is declared in the patent.

Table 2 reports some structural features for each level of detail that can be used in the Design for AM to obtain a structure that implements a given evaluation parameter. These structural features have been drawn from solutions presented in the literature.

| *Level of detail* | *Structural features* |
|---|---|
| Piece | Shape [7], multi-parts/materials [18], surface roughness [23], presence of embedded components/materials [16] |
| Internal structure | Repetitive structure with constant texture (e.g., lattice) [5], repetitive structure with different texture (e.g., Adaptive irregular lattice) [10], non-repetitive structure [16], shape of the single cell [9] |
| Infilling | Infilling (e.g., direction parallel, contour parallel, Hilbert curve, Fermat spiral, Sierpinski curve, Morton order, Peano curve) [34] |
| Wire, Powders | Wire diameter [15], bi-material wire (e.g., loaded thread, coaxial biomaterial wire) [38], diameters of the powders [24], form of the powders [23] |
| Material | Material inclusions [38], porosity [37], phase (only in metals) [36], auxetic |

| | |
|---|---|
| | disposition, to change the mechanical strength, i.e., modulo di Poisson, depending on the direction) [35] |

**Table 2**: Structural design features obtainable through AM.

To identify the most suitable structural feature to achieve each requirement, a step-divided procedure was defined. Its purpose is to use the scientific literature as a source of inspiration and knowledge to identify the structural features that best suit one's needs. In this way we want to avoid testing all those that a normal commercial simulation software makes available, saving analysis time and costs. Furthermore, structural features different from those implemented in the software can also be identified. The following paragraphs reports the descriptions of the steps of the proposed procedure:

1. Modelling the requirement to be achieved by defining constraints, boundary conditions, hypotheses and approximations.
2. Searching a structural feature, defined in a certain level of detail and allowing to realize a requirement, in the scientific literature. The selection is carried out by analogy, comparing the scenario and the boundary conditions of the model in the literature with those of the considered case study. In this case, the analogy may ask the designer for a different approximation effort, e.g., finding a structural feature already defined and tested in a piece made using AM, relying on available databases, e.g. [19], or taking inspiration from biological structures, e.g. [9] studied, by means of an electron microscope, the microstructure of the shell of a beetle, abstracting from it a microstructural cell for pieces to be made by AM.
3. Verifying the structural feature implemented in the piece through virtual simulation or real experimentation.

This procedure is repeated iteratively, as many times as many structural features are to be tested. Following this, the two structural features, which best achieve Requirement 1 and Requirement 2 respectively, are identified.

## 2.3 Implementing the Structural Features

The implementation of the structural features in the structure of the piece made in AM was mapped through two sub-steps: the formulation of the contradiction and its solution. The two sub-steps are described in detail below.

### *2.3.1 Formulating the contradiction*

Due to how the contradictions described in the analysed case studies from the literature, compared to the theoretical model of the physical contradiction of TRIZ, shown in Figure 1, the Condition 1 coincides with the structural feature 1. The Condition 2 coincides instead with the structural feature 2, while the Control parameter is associated with the design choice that the designer makes between the implementation of the structural feature 1 and the structural feature 2.

### *2.3.2 Solving the contradiction*

By analysing instead how the contradictions were resolved in the analysed case studies from the literature, i.e., by implementing the structural feature 1 to obtain the requirement 1, without invalidating the requirement 2 and vice versa, the analogies with two theoretical principles of separation, described below, are emerged.

**Macro-micro separation.** Structural feature 1 is defined at a different level of detail than structural feature 2. In this case, the critical issue to deal with is typically the implementation of the structural features of the lower level. If the latter does not affect the requirement of the other structural features, then both can be implemented to solve the contradiction. Otherwise, it is possible to replace at least one of the two structural features with another defined within the same level of detail or in another level. For example (see Fig. 2) the AM printing of the silica aerogel exploits the open porosity of this material to achieve the acoustic insulation (evaluation parameter)

[37]. In this case, the design of the structure coincides with the selection of the material. This material is compatible with a lattice structure since the extremely small size of the porosity does not affect the mechanical strength of the component.

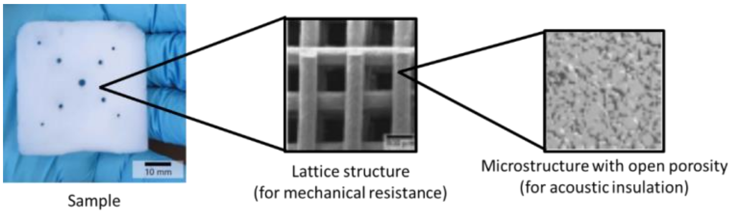


**Figure 2**: Example of macro-micro separation [37].

**Separation in space.** On the other hand, when the two structural features are defined at the same level of detail, then their implementation can take place as long as two distinct operational areas are identified in which the two structural features can be realized separately. [32] combined in space two different types of lattice structures, related to two different materials, to ensure mechanical strength and thermal insulation (see Fig. 3 left). To fulfil the same purpose [18] combined different materials according to an arrangement of alternating layers, obtained by means of selective laser melting (see Fig. 3 right). Similarly, [16] combined different materials, although only one material was made through AM, while the other, i.e. the wood has been incorporated into the printed structure.

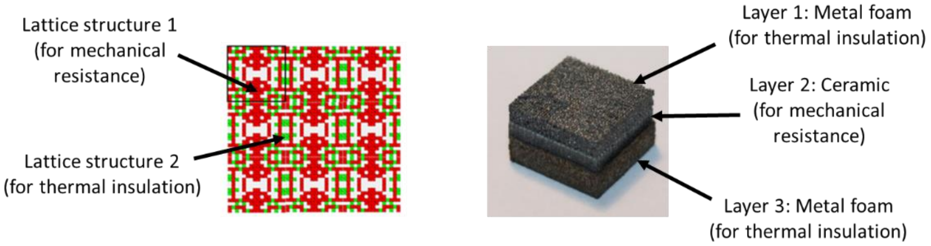


**Figure 3**: Examples of separation in space to combine (left) two lattice structures within the microstructure [32] and (right) two or more materials in the macrostructure [18].

The implementation of the structural features in the structure of the piece must be subordinated to boundaries conditions and design limitations. In this regard it is necessary to consider their compatibility with:

- The geometry and the characteristic dimensions of the structural features with the used AM technology.
- The fulfilment of the other secondary requirements.

Otherwise, it will be necessary to repeat STEP 2, by selecting other structural features, which once implemented ensure such compatibility. This process can be done iteratively.

## 3 CASE STUDY

The proposed method was applied to solve a contradictory design problem about a titanium dental prosthesis provided by Agliati s.r.l., a local company active in the production of dental implants and dental implantology for over thirty years. AM technology could allow to the company to save time, material and costs, while improving the customization service for customers. However, the technological limit of the surface quality of AM technology pushes the manufacturer towards post-production processing, using CNC machines for finishing holes in the denture, inside which the fixing pins are inserted. The positioning and locking of the printed prosthesis in CNC machining cause mechanical and thermal stress that can compromise the alignment of the holes with the mandible fixture.

### 3.1 Identifying the Contradicting Requirements

The design contradiction deals with the achievement of requirement 1 (i.e., mechanical resistance of the dental prosthesis during chewing, in which the denture is subjected to a compressive stress) and requirement 2 (i.e., thermal resistance of the dental prosthesis during the machining of denture holes with machine tools to avoid thermal expansion of the denture and therefore the loss of its positioning tolerances with the palate). Fig. 4 left provides a graphical representation of the design contradiction.

### 3.2 Identifying the Structural Features

To identify the solution to the denture microstructure design problem, a cubic sample was conceptually extracted from the framework and it is tangent to one of the holes (see Fig. 4 left). To consider both the two requirements, the optimization of the microstructure of the sample was obtained by fixing a distributed compression load on the two upper and lower surfaces of the sample and a distributed thermal load on the lateral surface of the sample. In the definition of the SF, the two loads were considered separately, first searching for the SF 1 to realize the Requirement 1 and then the SF 2 to realize the Requirement 2. Both SF1 and SF2 are the best options available to realize each of the two requirements. Both were chosen from the many options available in different levels of detail. In this phase, the CAD software nTopology was used since it allows to be used through a flow of functions called "blocks", to control of product design optimization on multiple levels of detail and to select different design options. The described sample was considered to reduce the computational time and costs during the simulations to identify the SFs among the available design options. These latter were also interpreted according to the different levels of detail of the Design for AM (see Fig. 4 right).

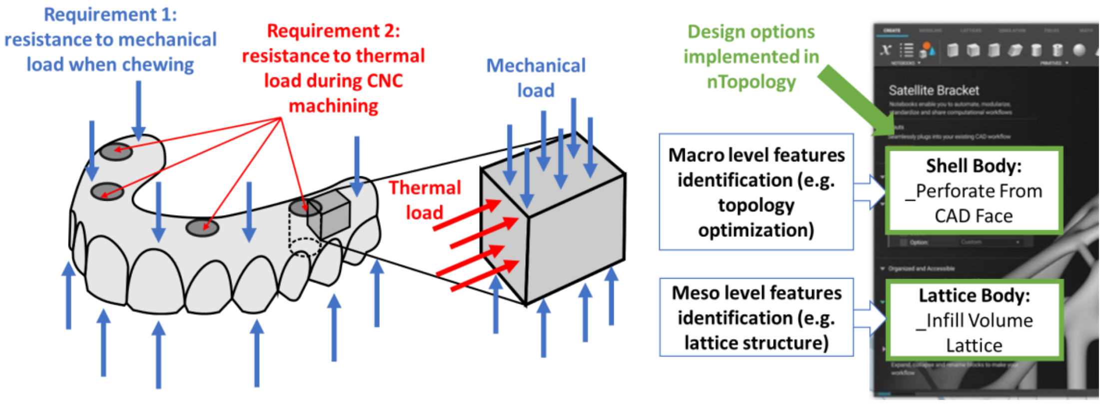


**Figure 4:** Graphical representation of the two requirements in the considered design problem and the considered sample (left). Provided interpretation of the design options provided by nTopology and the levels of detail (right).

Through the simulations in nTopology of the two load conditions considered, two different SFs emerged to achieve the two requirements, which are defined within two different levels of detail. In particular, SF1, to realize the Requirement 1, consists of a cellular structure (defined at mesolevel) called "Triply Period Minimal Surfaces Diamond", while SF2, to realize the Requirement 2, consists of an infill structure (defined at microlevel) called "Diamond fill".

### 3.3 Implementing the Structural Features

Since SF1 and SF2 are defined at different levels of detail, to solve the contradiction they were combined in the sample, using the macro-micro separation. As a result, SF2 was defined within SF1 in the considered sample (see Fig. 5 left). The main limitations of this implementation derive from the manufacturing process, having realized the sample with a laboratory-scale plastic 3D printer, i.e., a MakerBot Replicator + having a layer Resolution of 100 μm, a layer Height of 0.2 mm and a max power required of 182.4 W. For this reason, the used material is polylactic acid instead of titanium and the dimensions of the sample are much larger due to the resolution of the machine. The same structural features identified through simulation for the titanium prosthesis were considered but with an increased scale, not compatible scale with the dimensions of the prosthesis. At the same time, the expected performances (both mechanical and thermal) of the sample are considerably lower than those required for the titanium prosthesis.

## 4 TEST AND RESULTS

To test the effectiveness of the proposed method, the mechanical and thermal behaviour of the obtained sample, within which SF1 and SF2 were implemented through the principle of macro-micro separation, were tested. For simplicity, the sample on which the tests were performed was moulded in plastic material (i.e., PLA).

In order to compare the results obtained by testing the considered samples in terms of mechanical and thermal resistance, two other samples, identical to each other and based on a cellular structure (defined only at meso level), called "Diamond" defined at a single level of detail (see Fig. 5 right) and randomly selected from those available in nTopology, they realized by the same machine and with the same material. All the samples have a cubic shape and a side of 40 mm and the same mass, equal to 35 g (in the virtual model). The considered simplification, by using the plastic samples, does not invalidate the results of this test, since our goal is to evaluate, in this first phase, the validity of the method in identifying and combining microstructural characteristics (i.e., SFs) within a reference volume, regardless of the dimensions, material and the magnitude of the associated loads during the test.

Fig. 5 shows the two considered samples with the detail of their microstructures.

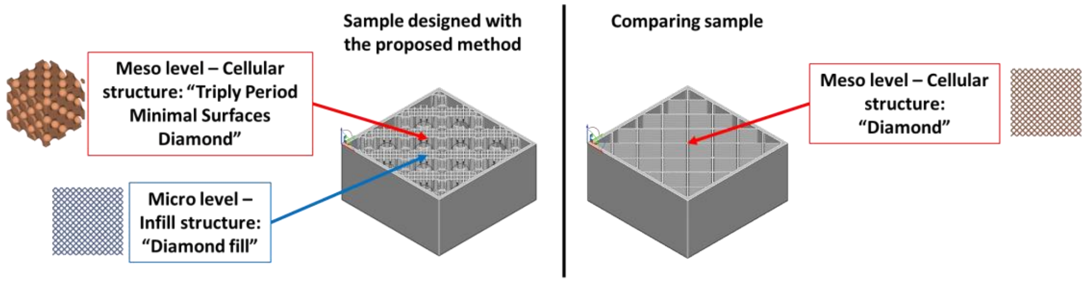


**Figure 5**: The two considered sample with the detail of their microstructures: the sample designed with through the proposed method (left) and the comparing sample (right).

The performances criteria to test the proposed solution are:

- The breaking load and deformation of the two samples, when they are subjected to the same mechanical load, to test the realization of requirement 1.
- The temperature in a certain point within the samples, when they are subjected to the same thermal load, to test the realization of requirement 2.

The hypotheses to demonstrate through the tests are that the Sample designed with the proposed method have higher breaking load and/or deformation than the comparing sample and a lower temperature in the considered point.

To test the mechanical behaviour, the samples (two of each type) were compressed inside a press in order to determine their breaking load. The considered test procedure follows the criteria presented in [8] and [11]. The used testing compression machine is a Galdabini with a maximum thrust equal to 50 kN. Two identical samples of each type were compressed and the obtained results were averaged. While to test the thermal behaviour, a virtual simulation using nTopology was performed, by setting a temperature of 100°C on a face of the sample and measuring the resulting temperature in a perpendicular direction. Fig. 6 depicts the results of the compression test (left) and the thermal test (right) on the two types of samples.

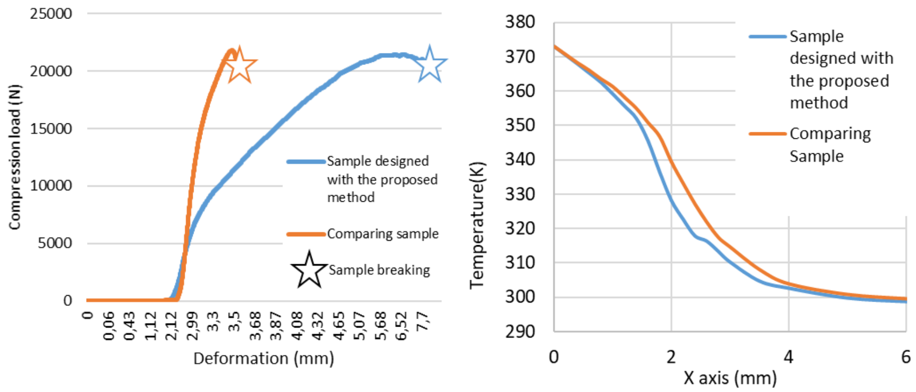


**Figure 6**: Results of the compression test (left) and thermal test (right) on the two types of samples.

As can be seen by Fig. 6, the two types of samples broke with approximately the same compression breaking load, but the sample designed with the proposed method obtained a much greater deformation than the comparing sample (+240%). The result of the thermal test showed instead that the sample designed with the proposed method has better insulating properties than the comparing sample since the temperature curve of the first is more squashed down than that of the second. These results have shown, as a first approximation, the advantages deriving from the use of the proposed method in providing an initial modelling of the problem before using traditional software to support Design for AM. Other studies in the literature have confirmed, albeit in a different way, the need for a preliminary analysis of the initial problem, or to use the tools within a structured methodological approach to guarantee more strategic results, especially for less experienced designers (e.g., [2]). In addition, these authors also confirmed the importance of intervening adequately in teaching, combining the more practical one, relating to FE tools, with the more theoretical one of design methods, aimed at stimulating students to use these tools more reasonably. Finally, the same advantages of a preliminary analysis to the FE analysis had already been demonstrated, by applying the same TRIZ method to this purpose, albeit to explore specific solutions to specific contradictory problems, albeit not related to AM (e.g. [13]).

## 5 CONCLUSIONS

To test the method, two different samples (one designed with the proposed method and the other not) tested by determining breaking load and thermal conductivity. The main limitations of this test are the material used (i.e., PLA) and the dimensions of the samples, due to the constraint of the resolution of the printing machine. In particular, the sample designed with the proposed framework consists of the combination of two microstructures at two different levels of detail, a cellular structure (i.e., Triply Perriodic Minimal Surface) to ensure high thermal transmission and thus reduce the risk of thermal and microscopic deformation (i.e., Diamond fill) to ensure the mechanical resistance.

The results of the test showed that the sample designed with the proposed method has better mechanical and thermal resistance than the comparing sample, by better solving the design contradiction. For this reason, these results confirm, at least initially, the effectiveness of the proposed method. For all these considerations, the method can have positive repercussions on Design for AM, encouraging the use of AM to solve contradictory problems. This is because this method has made it possible to expand the problem space, formalizing the contradictory problem with much more information, and the solution space, encouraging multilevel design and implementing the solutions in a more targeted manner. In this way, the application of the proposed method could also allow for the rationalization of resources in the AM, in terms of mass and energy, thus also having positive repercussions for environmental sustainability.

To confirm these first impressions, the future developments planned for the proposed method concern the expansion of the tests carried out, considering new case studies on products with different geometries, sizes and materials. At the same time there is also the intention to expand the theoretical knowledge base, expanding the analysed documentary base.

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