Title:
A Design Framework for Additive Manufacturing to Solve Design Contradictions

Authors:
Christian Spreafico, christian.spreafico@unibg.it, Università degli Studi di Bergamo
Filippo Colombo Zefinetti, filippo.colombozefinetti@unibg.it, Università degli Studi di Bergamo
Daniele Landi, daniele.landi@unibg.it, Università degli Studi di Bergamo
Daniele Regazzoni, daniele.regazzoni@unibg.it, Università degli Studi di Bergamo

Keywords:
Design for Additive Manufacturing, Optimization Method, Lattice Structures, TRIZ

DOI: 10.14733/cadconfP.2022.184-188

Introduction:
Optimization has been a significant aspect of design process: this step allows to increase product performance through algorithms that modify design parameters according to various mathematical theories. Recently, the increasing computational performance revitalizes optimization strategies in most of the CAD software. Now algorithms can redesign product shapes according to multiple parameters controlled by designers. At the same time, Additive Manufacturing (AM) has made possible to bring the complexity generated by CAD software to real products. Indeed, one of the clearest advantages of AM is the ability to generate objects with a much higher complexity than traditional manufacturing technologies. AM also proposes design at different levels of detail, taking into consideration a wide range of structural characteristics (e.g., external shape, lattice structures, infills, etc.). Consequently, enlarging the solution space allows designers to propose multiple solutions but, at the same time, intensifies the difficulty of control tens of design parameters. This problem is particularly serious during the design of products with multiple features at odds with each other. In this way, optimization algorithms and AM can offer the designer more chances to resolve contradictions in design by going beyond the psychological inertia of classic industrial design approach.

This paper proposes a Design for AM method that supports the resolution of design contradictions. It is based on the contextualization of the theoretical approach proposed by the TRIZ (Russian acronym for "Theory of Inventive Problem Solving") method [1] to solve contradictions by realizing a structural solution through AM. The main novelty lies in the association between the logic of multilevel design, which TRIZ uses to overcome a contradiction, and the structural features that AM allows to realize, also distributed on different levels of detail (e.g. shape, internal structure, infilling, porosity).

State of the Art:
In the literature, several Design for AM frameworks supporting the resolution of design contradictions, by fully grasping the potential of AM technologies, have been proposed (e.g. [4], [3], [7]). In particular, there are many examples of structures made of AM which at the same time guarantee different mechanical or physical qualities: for example, mechanical resistance and lightness [6] or mechanical resistance and acoustic insulation [12]. Many of them deal with a contradiction in a rigorous manner, through the approach proposed by the TRIZ method and propose solutions based on the structural characteristics that can be implemented in products made with AM. TRIZ method

exploiting this approach was used to solve contradictions in different fields of design, such as eco-design (e.g. [11]), forecasting (e.g. [8]), knowledge-based design (e.g. [9]).

The resolution of the contradiction was modeled by the TRIZ method through the separation principles of the control parameter [10]. These principles aim to highlight a structural configuration in which the two Conditions of the Control parameter are combined in such a way as to ensure the fulfillment of both requirements.

However, this approach has at least two main limitations. First, the contradictions (e.g., TRIZ method) are modeled too conceptually in comparison to the classic product design methods known by designers. Second, the search for solutions to contradictions does not take into consideration all the advantages in shape freedom and the structural weaknesses of additive manufactured parts at different detail levels (e.g., topology optimization, infill, multi-materials). The proposals of [7] and [2] are those that reach a higher level of resolutive detail. However, in the article by [7] the potential of the AM has been exploited only marginally at the macro level, with the shape optimization of the product. Instead, the approach of [2] has been more complete in formalizing the levels of detail to solve the contradiction, while marginally referring to AM technology.

The method proposed in this article is a contextualization of the TRIZ approach to the formulation and resolution of design contradictions in the context of emerging AM technology, which allows a greater possibility of creating physical and mechanical characteristics through various levels of design dimensions.

<u>Proposal:</u>
The proposed method has been divided into three main steps:

1. Identification of the two contradicting design requirements.
2. Identification of the most suitable Structural Features (SF), to be realized through design for AM (e.g. shape, internal structure, infill, porosity), to achieve requirement 1 and requirement 2.
3. Solving the contradiction by combining the Structural Features realizing requirement 1 (SF1) with the Structural Features realizing requirement 2 (SF2), within the structure of the product to be obtained through AM.

In the following sections the steps of the proposed method are presented in detail:

STEP 1 - Contradicting requirements definition
The first step of the proposed methodology consists in identifying two contradicting requirements that the product should guarantee. The requirements could have mechanical or physical nature: e.g., mechanical strength and lightness or thermal insulation and acoustic conduction.

STEP 2 - Structural features definition
In the second step, the structural features to be implemented on the product to realize the two requirements are identified. These features can be retrieved from different levels of detail since AM technologies allow to operate through hierarchical complexity.

Alternative structural features, defined at different levels of detail can be exploited to realize a certain requirement. Let's consider for instance mass reduction. It can be obtained, at the macro-level (level 1) by topology optimization, at a lower level of detail (level 2) through the use of lattice structures, at an even lower level (level 3), through a honeycomb infill, to the level of the constituent material (level 4). Another example is the solution provided by patent [5], to obtain a particular value of surface roughness of a hip prostheses made by AM, to reduce the welding times between the prosthesis and the bone. To realize this requirement, the authors worked on the shape of the constituent titanium powders (structural feature at 4th level), by realizing them through laser pyrolysis.

STEP 3 - Solving the contradiction by combining the identified structural features
The implementation of the identified structural features within the structure of the product to be realize through AM, is made through the resolution of the contradiction according to what explained by the TRIZ method, i.e., through the application of one of these two separation principles:

- Macro-micro division is used to combine, within the structure of the product, SF1 and SF2 when they are defined at different levels of detail (e.g., a lattice structure and a certain porosity of the wire). In this case, SF2 is implemented within SF1 or vice versa. The criticality to be addressed is typically the implementation of the structural feature of the lower level, to not compromise the realization of the requirement provided by the other SF.

- Space division is used to combine the SF1 and SF2 when they are defined within the same level of detail (e.g., two different kinds of lattice structure). Their combination take place within two district zones: one for SF1 and one for SF2. Within the reference volume the zones can be only two or more, as in a sandwich structure or in a network.

<u>Case study:</u>
The proposed method was applied to solve a contradictory design problem about a dental prosthesis provided by Agliati s.r.l., a local company. The proposed contradiction deals with the achievement of both mechanical resistance (requirement 1) and thermal resistance (requirement 2) in the prosthesis (see Fig. 1 Top-left), albeit a common structure cannot realize both of them. The CAD software nTopology, usable through a flow of functions called "blocks", was used since it allows to control the product design optimization across multiple levels of detail.

To identify the solution to the denture microstructure design problem, a cubic sample was conceptually extracted from the model of the prosthesis (see Fig. 1 Bottom-left). The different SFs that realize the requirement 1 and those that realize the requirement 1 have been selected among the design options available in nTopology. To do this, these latter have been interpreted according to the different levels of detail of the Design for AM (see Fig. 1 Right). 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 (see Fig. 1 Bottom-left).

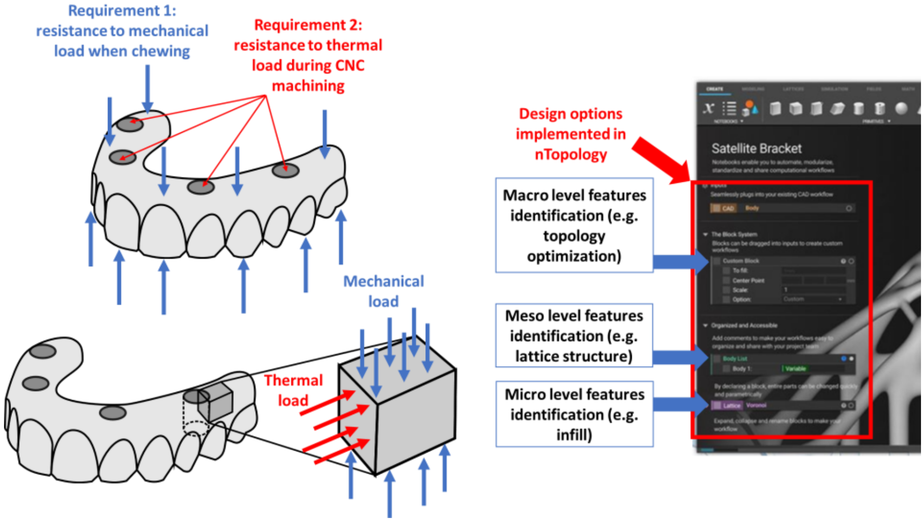

Fig. 1: Top-left: Graphical representation of the two requirements in the considered design problem. Bottom-left: the two requirements on the considered sample. Right: Provided interpretation of the design options provided by nTopology and the levels of detail on which to select the structural features according to the proposed method.

Through the simulations in nTopology of the two considered load conditions, 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”. Then 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. 2 Left).

To test the effectiveness of the proposed method, the mechanical and thermal behaviour of the obtained sample, within which SF1 and SF2 were implemented, were tested. For simplicity, the sample on which the tests were performed was moulded in plastic material (i.e. PLA). While, 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. 2 Right) and randomly selected from those available in nTopology. The different sample were realized by the same machine and have the same material, dimensions (40 x 40 x 40 mm) and mass (35 g).

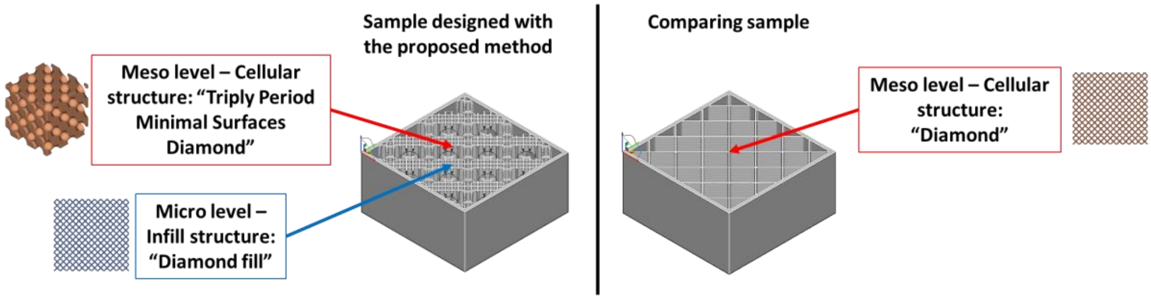

Fig. 2: The two considered sample with the detail of their microstructures: the sample designed with through the proposed method (left) and the comparing sample (right).

To test the mechanical behaviour, the samples (two of each type) were compressed inside a press (i.e. Galdabini with maximum thrust equal to 50 kN) in order to determine their breaking load. While to test the thermal behaviour, a virtual simulation using nTopology was performed. During this simulation, the temperature on a face of sample was set equal to 100°C and the ambient temperature was set to 25°C and the resulting temperature within the temperature was measured in a direction perpendicular to the hot face.

As results, the two types of samples broke with approximately the same compression breaking load (see Fig. 3 Left), 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 (see Fig. 3 Right).

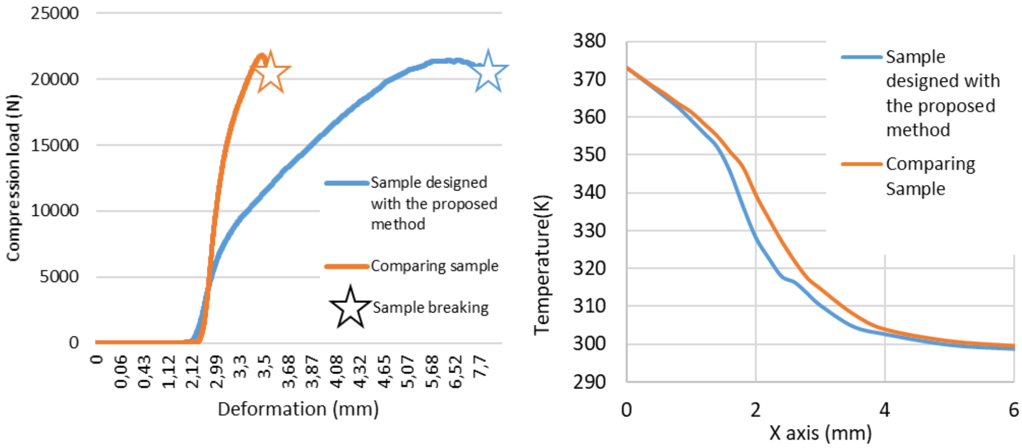

Fig. 3: Results of the compression test (left) and thermal test (right) on the two types of samples.

Proceedings of CAD'22, Beijing, China, July 11-13, 2022, 184-188

Conclusions:

This study proposed a Design for AM method for solving contradictory design problems, based on the contextualization of the TRIZ method in the field of AM. The main objective of this work lies in guiding a designer during the Design for AM, making sure that she/he does not base his design on the immense design potential that the software supporting Design for AM and AM technologies make available, but can manage them actively, with greater awareness of the design requirements. In addition, the proposed method is an invitation to exploit such potentialities of AM to respond to contradicting problems that would otherwise not be solved, by realizing a product with other technologies. The great advantage of the AM, which has been exploited for the proposed method, is in fact the possibility to design a structure at different levels of detail and to, through the proposed method, combine the solutions found in the different levels to resolve the contradiction. The results of the considered case study showed that a sample designed with the proposed method has better mechanical and thermal resistances (i.e. the considered contradictory requirements) than the comparing sample, by better solving the design contradiction. This was possible by implementing structural solutions defined at different levels of details. Future developments of the method concern the research and rigorous classification of structural features in relation to the strategies used to solve contradictory problems, and their detailed experimentation.

Acknowledgements:

The authors want to thank Agliati s.r.l. especially Debora and Guido for their priceless contribution.

References:

[1] Altshuller, G. S.: Creativity as an exact science: the theory of the solution of inventive problems. Gordon and Breach Science Publishers, New York, 1984.

[2] Caputi, A.; Russo, D.; Rizzi, C.: Multilevel topology optimization. Computer-Aided Design and Applications, 15(2), 2018, 193-202. https://doi.org/10.1080/16864360.2017.1375669

[3] Kretzschmar, N.; Chekurov, S.: The applicability of the 40 TRIZ principles in design for additive manufacturing, Annals of DAAAM & Proceedings, 29, 2018. http://dx.doi.org/10.2507/29th.daaam.proceedings.128

[4] Lang, A.; Gazo, C.; Segonds, F.; Mantelet, F.; Jean, C.; Guegan, J.; Buisine, S.: A proposal for a methodology of technical creativity mixing TRIZ and additive manufacturing, International TRIZ Future Conference, Springer, 2019, 106-116. https://doi.org/10.1007/978-3-030-32497-1_10

[5] Morris P.J.: Method for making a three-dimensional object, International Patent WO2015121369A1. World Intellectual Propriety Organization, 20 Aug. 2015.

[6] Pelanconi, M.; Ortona, A.: Review on the design approaches of cellular architectures produced by additive manufacturing, International Conference on Additive Manufacturing in Products and Applications, Springer, Cham, 2020, 52-64. https://doi.org/10.1007/978-3-030-54334-1_5

[7] Renjith, S.C.; Okudan Kremer, G. E.; Park, K.: A design framework for additive manufacturing through the synergistic use of axiomatic design theory and TRIZ, IISE Annual Conference, 2018.

[8] Spreafico, C. Quantifying the advantages of TRIZ in sustainability through life cycle assessment. Journal of Cleaner Production, 303, 126955, 2021. https://doi.org/10.1016/j.jclepro.2021.126955

[9] Spreafico, C., Russo, D., & Spreafico, M. Investigating the evolution of pyrolysis technologies through bibliometric analysis of patents and papers. Journal of Analytical and Applied Pyrolysis, 105021, 2021. https://doi.org/10.1016/j.jaap.2021.105021

[10] Spreafico, C., & Spreafico, M. Using text mining to retrieve information about circular economy. Computers in Industry, 132, 103525, 2021. https://doi.org/10.1016/j.compind.2021.103525

[11] Stratton R.; Mann D.: Systematic innovation and the underlying principles behind TRIZ and TOC, Journal of Materials Processing Technology, 139(1–3), 2003, 120-126, https://doi.org/10.1016/S0924-0136(03)00192-4

[12] Zhao, S.; Siqueira, G.; Drdova, S.; *et al.*: Additive manufacturing of silica aerogels, Nature, 584(7821), 2020, 387-392. https://doi.org/10.1038/s41586-020-2594-0