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TOPOLOGY OPTIMIZATION IN RAPID INVESTMENT CASTING OF A TRIANGULAR BRACKET

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Abstract: Despite its popularity, the traditional investment casting process requires significant time and expense to prepare tools for master pattern. The tool making process is based on machining on CNC systems, directly based on CAD/CAM data. This method of production is more justified in large-scale and mass production. Recently, Rapid Investment Casting (RIC), which represents the integration of Additive Manufacturing (AM) technologies with the conventional investment casting process, has been increasingly used. Presently, almost all commercialized AM techniques have been employed to produce casting patterns with varying success and many AM solutions in investment casting are being used by various industries and researchers. Such advantages provide unlimited opportunities in the cast part design and enable the use of advanced design tools especially advanced optimization tools like topology optimization (TO). In this study, design guidelines for RIC are developed through integration of TO with design for investment casting and design for AM principles. Accent of study is placed on description of topology optimization of a triangular bracket, in other words, mass reduction with equally Von Misses stress distribution taking into account type of material, permissible load capacity as well as constraints. Optimization is conducted within SolidWorks 2022 Topology Study module with mass reduction of 57,89 [%], compared to the initial design.
Keywords: Topology optimization, investment casting, design for Additive Manufacturing, Finite Element Analysis, triangular bracket

1. INTRODUCTION

The development of CAD/CAM technologies, and later Additive Manufacturing (AM) technology, enabled the production of precision aerospace parts of highly complex structures and shapes. Increasing quality, productivity, profitability and conformity to ecological criteria require further rationalization and optimization of conventional technologies for the production of aerospace parts through the development and application of new technologies [1,2]. This also applies to investment casting foundries which have the ambition to produce demanding, complex and high quality castings for the use in aerospace engineering. Their development requires appropriate innovations, application of the latest technological knowledge and information technology [3-5].

The term Rapid Investment Casting (RIC) represents the employment of AM technologies in investment casting. The designing costs as well as the metal tools manufacturing costs for the development of master patterns can be overcome by applying AM technologies. The employment of AM technologies also results in shorter casting time while providing the same quality. AM has been particularly effective in prototyping, as well as in single and small-scale productions. A large number of cost-effective solutions for investment casting of complex parts employing additive technologies have been reported in the literature so far [7].

Rapid investment casting (RIC) based on AM can easily fabricate complex patterns and allow a significant amount of time and cost savings [8]. Thanks to such benefits, the application of RIC ranges from the casting of jewellery, sporting equipment and medical implants to high-performance parts utilized in injection moulding, die casting and the automotive and aerospace industries [9].

To date, a variety of RIC solutions have been developed by industrial and academic researchers, and RIC solutions involving pattern fabrication can be classified into two categories: (1) direct AM of patterns and (2) indirect AM of patterns. For the direct AM of patterns, both wax and non-wax parts can be directly 3D-printed as patterns for investment casting. In the indirect AM approaches, IC patterns are often produced using AM-fabricated moulds or soft tooling, i.e., room temperature vulcanized (RTV) silicone rubber moulding, fabricated from AM master patterns [1-3].

This analysis encompassed the prototypical manufacturing of the master pattern, and the results of the analysis confirm the advantages of manufacturing the master patterns by direct approach

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

in the cases of prototype and single production. As for a small-scale production, up to several dozen pieces, the optimal choice would be to apply the indirect approach of master patterns manufacturing by injection moulding into silicone rubber moulds. In large-scale and mass-production cases, the advantage undoubtedly lies in conventional investment casting [9].
In recent years, structural optimization has been recognized as a very important tool in the product design process and is a field of research that deals with the creation of product construction, from a certain type of material, which aims to maintain a certain load in the best possible way. Structural optimization methods can be grouped into: topological optimization, dimensional optimization and shape optimization, Figure 1.

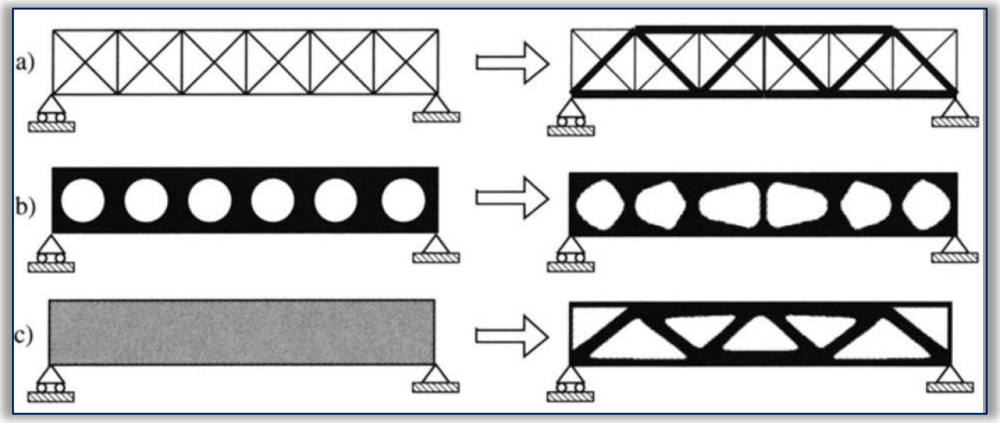


Figure 1. Illustration of a truss model and its different categories of structural optimization by: a) size, b) shape and c) topology [10]

Taking into account all types of structural optimization, it is necessary to point out that topological optimization represents the most complex type of optimization (hence the biggest savings here) due to the largest number of variables that participate in the optimization process. This type of optimization is applied at the initial stage of the design process, while the optimization of dimensions and shape is applied at the detailed design stage.
Besides lead-time and production cost reduction, material saving and part optimization are also important goals in industry. TO is an advanced tool to achieve such goals. Although TO has been well developed for decades, it has not been widely applied in industry due to the limited manufacturability of TO parts with conventional fabrication processes. However, TO relates well with AM due to its “freeform” aspect, which does not require any extra tooling to produce complex geometries generated by TO.
A typical TO problem involves four important concepts: (1) design space, (2) objective, (3) constraints, and (4) design variables. Design space describes the allowable region within which the design exists. An objective defines a physical quantity that needs to be maximized or minimized, such as stiffness and compliance. Constraints include the limits that the optimization solution must satisfy, such as maximum volume fraction and displacement. TO is solved based on Finite Element Method (FEM), by which a design space is discretized into finite elements [11-13].

2. MATERIAL AND METHODS

A proposed topology optimisation design flowchart for RIC patterns is shown in Figure 2, which involves the following important steps.

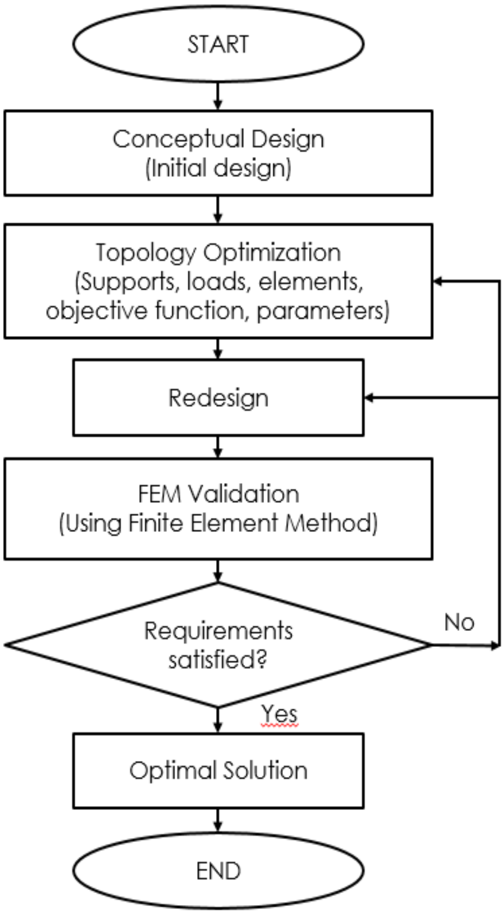


Figure 2. Design flowchart for topology optimization

Design of initial CAD model

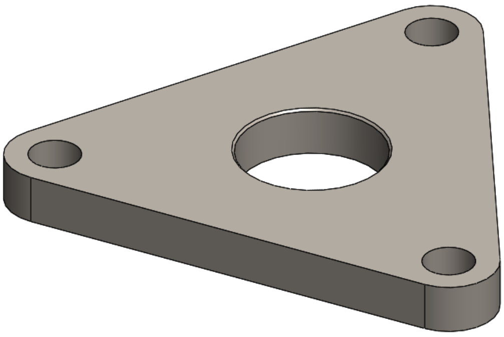
The pattern design for a RIC process always starts with a 3D computer-aided design (CAD) model representing the geometry of a metal part. The 3D model of triangular bracket was created in 3D CAD software package SolidWorks 2022.

In addition, application information, such as casting material, loads, and boundary conditions must be known. DIN Steel Stainless 1.400 (X6Cr13) was chosen as the material of the triangular bracket for topology optimization. Table 1 gives the characteristics of the chosen material.

For this research purposes, the 3D model was simplified and reliefs on model both sides were not created. After adding the material, the mass of the modeled triangular bracket is mi = 0.399 [kg].

Table 1. DIN Steel Stainless 1.400 (X6Cr13) material characteristics

DIN Steel Stainless 1.400 (X6Cr13)	
Yield Strenght	230 [MPa]
Tensile Strenght	400 [MPa]
Mass Density	7700 [kg/m^3]
Elastic Modulus	220000 [MPa]
Poisson's Ratio	0,28



a) b)

Figure 3. a) Stainless steel casting; b) SolidWorks 3D model of triangular bracket

Analysis of the initial model using the FEM

By analyzing the stress state, the observed design is evaluated and its deficiencies are sought based on the set criteria that the structure must meet in terms of functional and mechanical characteristics. The parameters of the finite elements for the presented study are shown in table 2, while FFEPlus was chosen as the type of algorithm for solving the task.

A fixed support is defined through three small through holes, and a total force of F = 3000 [N] acts through the large through hole, Figure 4.

Table 2. Mesh parameters

Mesh type	Solid Mesh
Mesher used	Standard mesh
Jacobian points	4 points
Mesh quality	High
Total nodes	13268
Total elements	8064
Maximum Aspect Ratio	8.3275

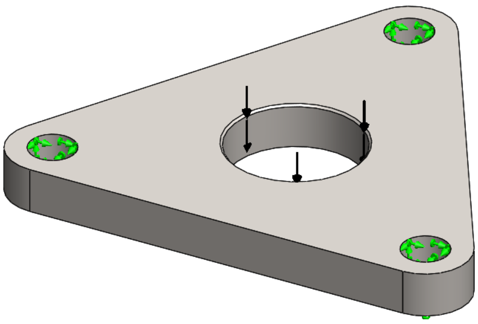
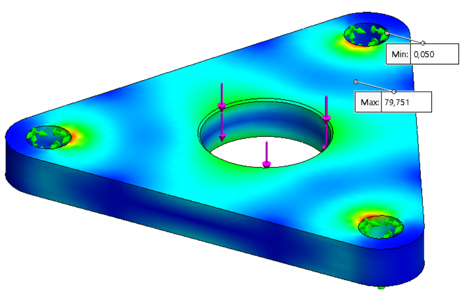


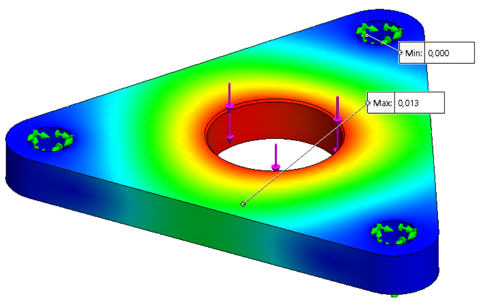
Figure 4. The design and load and boundary conditions

The analysis leads to the conclusion that the mass of initial design of the triangular bracket can be reduced if the stress distribution is taken into account, as well as the value of the target facor of safety, which is FOS ≥ 2, Figure 5.

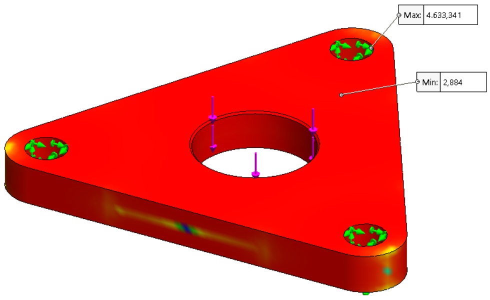
ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665



a) Von Mises Stress



b) Displacement



c) Factor of Safety (FOS)

Figure 5. Analysis of the initial 3D model using the FEM

Topology optimization and redesign

The first step of TO is to identify the design space and the non-design space, referring to the region that needs to be optimized and that should remain unchanged, respectively. The setup for a common TO task includes defining material properties and interactions, adding loads and boundary conditions, and determining objective(s) and constraints. For a mechanical loading application, the typical objective is to minimize the compliance or maximize the stiffness of the system, and the most important constraint is the volume fraction.

SolidWorks offers size, parametric shape and topology optimization. Regarding the TO, it uses the traditional compliance TO with the SIMP method when mass, stiffness, and displacement can be used as objective functions. Furthermore, it offers member size, mold (pull direction), and planar symmetry in addition to the standard manufacturing constraints. The optimized models consist of faceted geometries. Von Mises stress and displacement plots can be created with the plot of element density distribution.

After the analysis of the initial design, the triangular bracket is imported into the SolidWorks 2022 Topology Study module, where it is necessary to define the following parameters:

Table 3. Topology study parameters

Goals	Best Stiffness to Weight ratio
Constrains	Reduce mass
Preserved Region	5 [mm]
Half Symmetry	Middle Plane
Mesh	Deafult values

The second step is the refinement and revision of the TO output geometry. Refinement is necessary because the TO results are often a collection of discretized elements with coarse surface finish. Revisions are needed too to modify the result for a geometry suitable for fabrication and casting. The redesign procedure could vary depending on the capability of different design tools. Designers need to have a comprehensive understanding of the advantages and disadvantages of different design tools and determine the best option for the redesign. Typically, there are three important considerations during redesigning process: to include part requirements, IC constraints, and design for AM principles into TO workflow respectively.

- Part requirements: part rationale, practical applications and geometric requirements.
- IC design rules: wall thickness, uniform section, rounded edges, maximum ratio of hole depth to diameter for patterns, directional
- AM design rules: build volume, extrusion temperature, dimensional accuracy, printing speed, minimum feature size, layer height, support, shell thickness, infill density, build direction and warping.

The non-design space included three small holes and the region around big hole. The rest of the triangular bracket geometry was defined as the design space. Three topological optimized geometries were generated with 40%, 50%, and 60% mass reductions, respectively, as (Fig. 6). The output geometries were exported as smoothed mesh files, saved as graphic body and individually opened in SolidWorks 2022 for redesign.

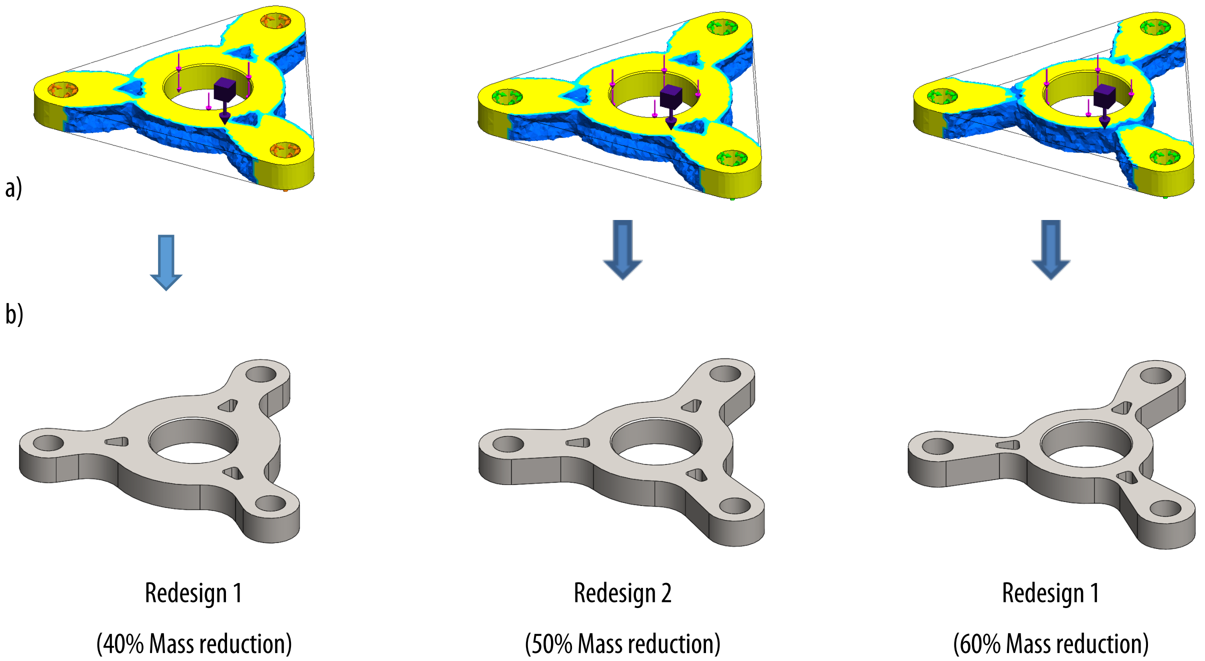


Figure 6. Mass reduction results: a) TO output geometries, b) final redesign

3. FEM VALIDATION

Geometrical revisions were performed afterward following the previously mentioned redesign rules, including wall thickness, rounded edges and hole size. After the revisions, FEA for fi[nal designs were then carried out in SolidWorks 2022. Fig. 7 showed the comparison of FEA results between the original design and three optimized designs. In addition, a 2 [%] global shrinkage allowance for cast stainless steel was applied to all geometries.

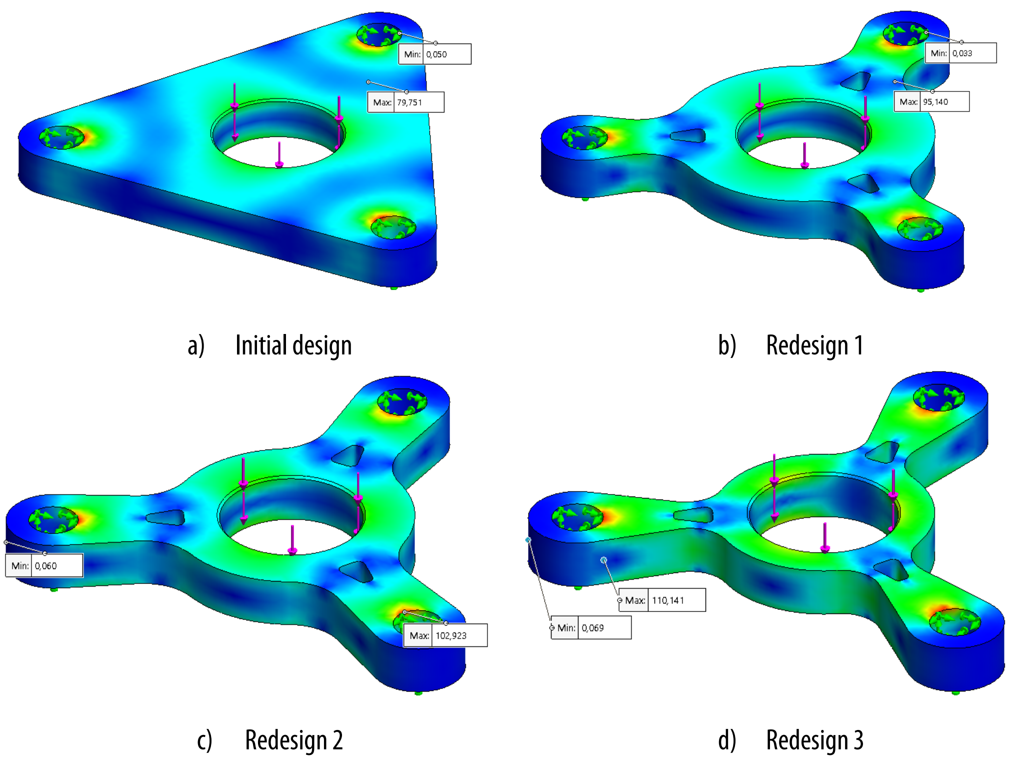


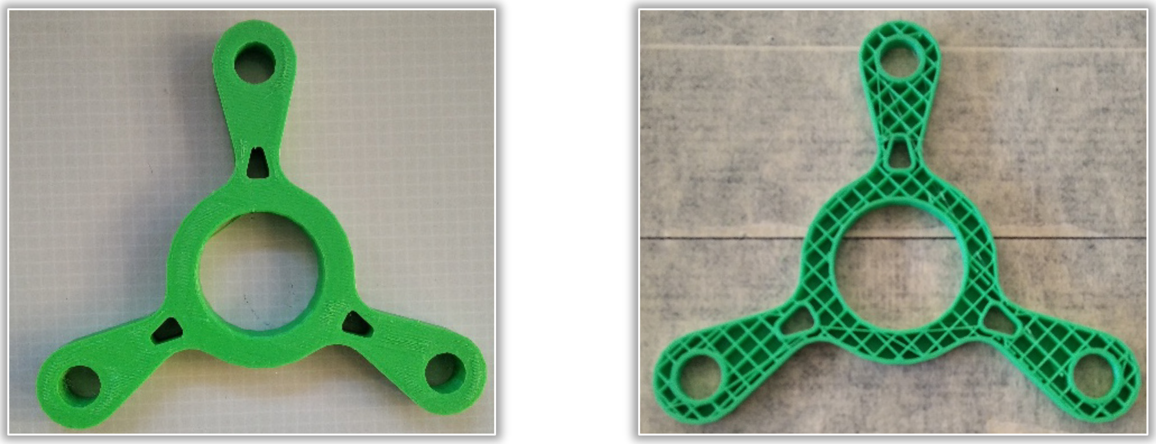
Figure 7. Von Mises Stress comparison: a) 79,751 [MPa], b) 95,140 [MPa], c) 102,923 [MPa] and d) 110,141 [MPa]

4. ADDITIVE MANUFACTURING OF THE OPTIMAL TRIANGULAR BRACKET DESIGN

A commercial PLA filament was used to fabricate the optimal design of triangular bracket patterns on a Creality Ender 6 3D printer. The printing parameters, Table 4, were determined based on the aforementioned design for AM rules. An optimal build direction was chosen to minimize the need for support structures and to ensure good printing quality. Optimal pattern 3D model was converted to the STL extension. Preparation for 3D printing was carried out in Creality Slicer software.

Table 4. 3D printing process parameters

Parameter	Setting
Model material	PLA
Layer thickness	0,2 [mm]
Printing temperature	220 [°C]
Printing speed	50 [mm/s]
Infill density	20 [%]
Tip popune	Grid
Manufacturing time	75 [min]
Material consumption	13 [g]



a) b)

Figure 8. a) PLA model redesign 3, b) infill density 20 [%]

5. RESULTS AND DISCUSSION

The topological optimization was done through 3 iterations, Table 5, where the analysis of the results leads to the conclusion that the optimal solution was obtained in the third iteration. According to the obtained data, the total mass reduction in relation to the initial construction can be calculated according to the following formula:

$$\Delta m = \left|\frac{(m_i - m_o)}{m_i}\right| \cdot 100\%$$

Table 5. Results of the topological optimization of the tringular bracket

Initial design	Redesign 1	Redesign 2	Redesign 3
	Target Mass reduction by percentage		
	40[%]	50[%]	60[%]
	Topology optimisation results		
m_0 = 0,399 [kg]	m_0 = 0,253 [kg]	m_0 = 0,224 [kg]	m_0 = 0,168 [kg]
	Δm = 36,59 [%]	Δm = 43,86 [%]	Δm = 57,89 [%]
VM Stress = 79,751 [MPa]	VM Stress = 95,140 [MPa]	VM Stress = 102,923 [MPa]	VM Stress = 110,141 [MPa]
FOS = 2,88	FOS = 2,41	FOS = 2,23	FOS = 2,08

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

In order to make the best use of the geometric design freedom provided by this method, it is important to fully understand the manufacturing constraints involved in this RIC process. In this study, topology optimization was applied and followed by geometric redesign based on a set of design rules for additive manufacturing and investment casting. In spite of a reduction in weight, all redesigns were shown via FEA to have better mechanical performance than the initial design. The important conclusions of this study include:

- By combining topology optimization of cast parts and additive manufacturing of wax patterns, there is significant potential for the casting of lightweight and structurally optimized metal components for mechanical applications.
- Design for additive manufacturing and investment casting principles play a crucial role in the design of wax patterns for RIC. Designers need to trade off different rules and determine the optimal design procedure to achieve the desired design requirements of patterns.
- The TO in SolidWorks is quite easy, but its TO module offers limited capabilities and options. The supported objective functions are stiffness, mass, and displacement, while displacement, mass, frequency, stress, and FOS can be used as constraints. Furthermore, it offers member size, mold (pull direction), and planar symmetry in addition to the standard manufacturing constraints. The TO module creates stress, displacement, strain, and FOS plots for the optimized designs.

6. CONCLUSION

The implementation of topology optimization in the cast part design for RIC enables the casting of metal parts with reduced weight yet improved mechanical performances. However, topology optimization outputs are generally not ready for casting but need geometric refinement and revision based on corresponding manufacturing constraints. Although topology optimization is a mature design approach, using current topology optimization and CAD software to design parts for casting is still time-consuming. Multiple commercial tools are used iteratively to get acceptable final designs, which might lead to cost and time justification problems. The analysis of the initial design of the triangular bracket revealed that the existing design has certain deficiencies that can be compensated for by applying topological optimization in the early design phase. On the basis of the presented results, it is concluded that there was a significant saving in material of as much as 57.89 [%], that is, by 0.231 [kg], compared to the initial design. In addition, these savings entail savings in both handling and transportation costs. Variations of different optimization algorithms, as well as different variations of finite elements in order to obtain more precise results, can be mentioned as future directions of research.

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ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665
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