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A Review of Topology Optimisation Software for Additive Manufacturing: Capability Comparison

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***Abstract*—The topology optimisation method has gained significant attention in recent decades due to the extensive development and implementation of additive manufacturing, an advanced technology applied to fabricate complex geometries and structures. By following the topology optimisation methodology, the existing geometry can be effectively optimised by minimising or maximising objective functions, such as stiffness, volume, or weight reduction. This paper provides an overview of the topology optimisation algorithm and compares the capabilities of computer-aided software designed to conduct topology optimisation procedures. Four different software are analysed using case studies from various industries. The case study models are categorised based on important parameters for the topology optimisation and evaluated in terms of availability, optimisation method, objective function, and other factors.**

Keywords—structural optimisation, topology optimisation, computer-aided-design, finite element analysis, additive manufacturing

I. Introduction

Computer-aided topology optimisation is an increasingly popular and reliable tool for improving the quality and efficiency of the development process of a wide range of important components [1]. The optimised parts generated using this method demonstrate high-performance mechanical properties but often involve complex geometry and internal structures which are extremely challenging to produce using conventional manufacturing processes such as milling or turning [2]. In recent decades, topology optimisation has proved to be a powerful tool, particularly when combined with additive manufacturing methods. It has also enjoyed rapid growth and popularity in the aerospace [3], automotive [4], and medical industries [5].

Topology optimisation (TO), a subset of structural optimisation (SO) [6], is a method providing possibility to create an optimal geometrical structure by reducing and rearranging the material distribution. This is achieved by adjusting various structural properties and considering constraints, loads, and boundary conditions [7],[8]. The space domain of the structure applied to optimisation procedure is discretised into a significant number of small finite elements. An appropriate mathematical algorithm determines the density distribution of the structure by verifying which elements should contain material and which are considered void [9]. To solve the optimisation problem [10], several algorithmic approaches, such as solid isotropic material with penalisation (SIMP) or level set function (LSF), are developed and included into majority of today's computer-aided topology optimisation software [11]. Topology optimisation software, whether integrated into software or standalone [12], follows a defined methodological approach that generates a geometrical structure with an optimal density distribution after several iteration runs. In this paper, three topology optimisations included in Ansys Mechanical [13]-[18], Fusion360 [19]-[24], Solidworks Simulate [25]-[29], and stand-alone nTopology [30]-[33] are analysed and compared in terms of implementation and performance capabilities.

II. Optimisation Methodology Overview

The industrial usage of topology optimisation must be able to simulate and optimise different mechanical states to achieve the best possible design which is as good as possible under given functional conditions. As shown in Fig. 1, the optimised design is still uncertain at the beginning of the process but requires the necessary boundary conditions to be generated.

A. Structural Optimisation

Topology optimisation belongs to the group of structural optimisations, which also includes sizing optimisation and shape optimisation (can be seen in Fig. 2). Size optimisation refers to the optimisation of specific design parameters in a fixed defined range (Fig. 2a). In shape optimisation, the design variables describe the shape and location of the

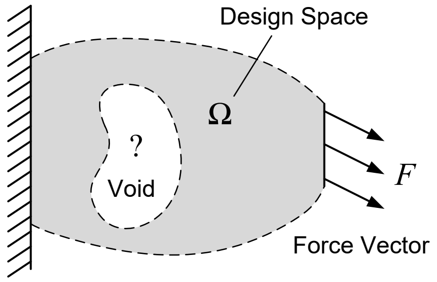

Fig. 1. Illustration of structural optimisation problem.

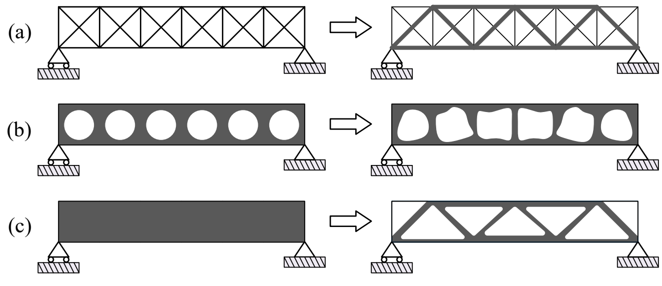

Fig. 2. Categories of structural optimisation: (a) sizing optimisation; (b) shape optimisation; (c) topology optimisation [6].

boundary of a known structure (Fig. 2b). Finally, topology optimisation is a mathematical algorithm providing optimisation of material distribution within a defined area where appropriate constraints such as bearing positions, fixed geometry areas, and also applied forces, are predefined in advance (Fig. 2c). Size and shape optimisations are usually applied relatively late in the design process compared to topology optimisation.

B. Topology Optimisation Mathematical Approach

A conventional way to mathematically represent a structural optimisation problem is an objective function $f(x,y)$, where (x) is a design variable and (y) is a state variable. The objective function is used to classify designs and usually includes parameters such as weight, compliance, and displacement. The design variables are related to the structure geometry and the selected material, while the state variables constitute the behaviour of the structure, such as tension and elongation. According to [7], the design constraints include a variety of restrictions and limitations, which can generally be subdivided into three categories: behavioural, design and equilibrium constraints. The design constraints are included in the design variables whereas the behavioural constraints affect the state variables. The equilibrium constraints are involved in the discretisation of the design domain formulated as a linear problem and are represented as follows [7],[8].

$$K\left(x\right)u = F\left(x\right) \tag{1}$$

where $K(x)$ is the structure stiffness matrix; u is the displacement vector; $F(x)$ is the force vector.

Following classical compliance-based topology optimisation, the objective function quantifies the structure stiffness through the compliance $f(x,y) = c$. The design variable x in the design domain Ω is a fictitious density $(x = \rho_e)$, where $\rho_e = 1$ for material and $\rho_e = 0$ for void space [10]. The optimisation problem is defined mathematically as

$$\frac{\min}{\rho} : F = F\left(u\left(\rho\right),\rho\right) = \int_{\Omega} f\left(u\left(\rho\right),\rho\right) dV \tag{2}$$

$$\text{subject to: } g_0\left(\rho_e\right) = \int_{\Omega} \rho_e dv - V_0 \tag{3}$$

$$g_i\left(\rho_e, u\left(\rho_e\right)\right) \le g_i^*, i = 1,...,M \tag{4}$$

$$K\left(\rho_e\right)u = F\left(\rho_e\right) \tag{5}$$

$$\rho_e = \begin{cases} 0 \\ 1 \end{cases}, e = 1,...,N \tag{6}$$

The discrete formulation, however, encounters numerous difficulties, therefore, continuous variables are used instead of fixed variables. The density values of the elements can now have a value between zero and one:

$$0 < \rho_{\min} \le \rho_e \le 1, e = 1,...,N, \rho_{\min} \ne 0 \tag{7}$$

The most representative methods for solving this problem in current topology optimisation software and tools are SIMP method and LSF [11]. SIMP replaces the integer variables with continuous variables with an additional penalty. The design problem is formulated as a size problem where the stiffness matrix now depends on the material density. Although, the solution leads to an optimisation of the design consisting of elements with or without material. All element values vary from *zero* to *one*. The *zero* value is related to emptiness whereas *one* shows that the material is

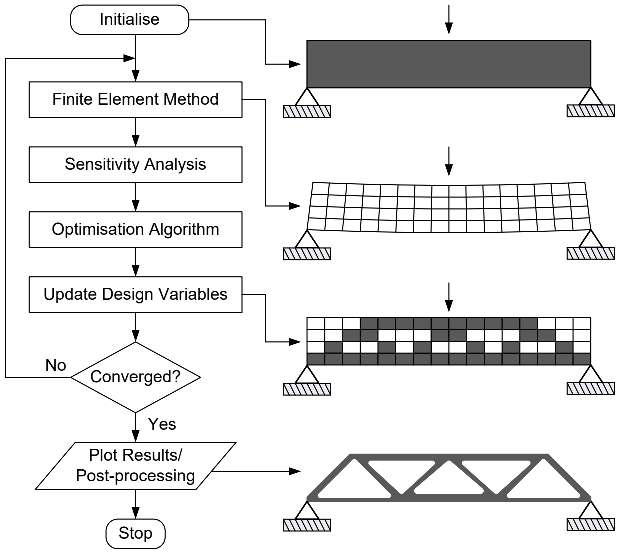

Fig. 3. Procedure of topology optimisation [34].

present. The values between *zero* and *one* are corresponding to pseudo-materials appearing. The LSF method is specified by separating the design space into raster as design variables with differing values. Furthermore, the prescribed threshold values truncate the LSF at a unique layer, where the topology model is represented by the set of layers having a value higher than the threshold. [11]. Given the complexity of these calculations, there are several software developers who solve this problem with the help of this algorithm.

C. Computer-Aided Topology Optimisation Method

In contrast to the classical analytical approach, in which a geometry design is first created on the basis of engineering mechanics and tested by finite element analysis afterwards, the topology optimisation procedure, as can be seen in Fig. 3, avoids several manual optimisation cycles and generates an optimised geometry at the beginning of the development process [6]

For topology optimisation, a displacement-based finite element analysis and then the optimal density distribution algorithm are applied. As with the traditional design approach, the process starts with an initial design that has defined boundary conditions. Afterwards, the density distribution is determined using the finite element method and the compliance of the structure is calculated based on. Since this is an iterative process, it is repeated until a convergent result is obtained. Once convergence is complete, the result must be evaluated [6],[34].

III. Software Review

Tyflopouls and Steinert [12] have analysed different stand-alone and integrated software for topology optimisation purposes. They reported that about 31% of software is released under open source licence and freely available for users. Other software is offered on the market as commercial products. However, 44% of commercial topology optimisation software provides an option of free licence for students and academic use. From the variety of software enabled to perform topology optimisation, four available products (Table I) were selected to study their capabilities and also to compare differences.

A. Ansys – Structural Optimisation

Ansys Structural Optimisation is a module in Ansys offering supports of size, parameter shape and topology optimisation and includes lattice and non-parametric shape

TABLE I. REVIEWED TOPOLOGY OPTIMISATION SOFTWARE

Software	Module	Company
ANSYS	Structural Optimisation	ANSYS, Inc
Fusion360	Shape Optimisation	Autodesk
Solidworks	Simulation	Dassault Systémes
nTopology	Simulation	nTopology

optimisation. SIMP and LSF are used for objective functions in this module [13],[14]. Ansys Structural Optimisation module is widely used in the aerospace industries, for example, to develop unibody quadcopters [15], air brake bracing beams [16], and latching components of hatch doors [17]. The module is also intensively applied in the automotive industry (for example, the transmission housing of a Baja racing car [18]).

In [15], Nvss et al. provided an detailed description of development of a new body of a quadcopter. The goal of this project is to optimise the body of a quadcopter, also called unmanned aerial vehicle (UAV). The optimised body should consist of a single part to minimise the assembly errors and the assembling time. Furthermore, the task was to reduce the weight of the body as much as possible by keeping the total weight below 2kg, otherwise the structural performance would be inadequate. For this purpose, they used the computational topological method approach through a number of iterations , as shown in Fig. 4, from the initial geometry stage up to the finally optimised part which was experimentally tested. The final design has a specially preserved compartment in the part centre for installation of electronic components. The design has also four designated areas for the propeller motor allocation.

The result of the finite element method with Acrylonitrile Butadiene Styrene (ABS) shows a total deformation of 4µm and stress distribution of 0.1MPa. Through Ansys, the SIMP method is used with stiffness maximation in consideration of mass reduction as objective functions Fig. 5 shows a converged geometry after several iterative topology optimisation runs.

Afterwards, the generated component is remodelled for evaluation. Subsequently, a fatigue test is performed, which represents the lifetime of the model. Compared to the initial component, the mass is significantly reduced while maintaining a comparable stress distribution. Finally, the

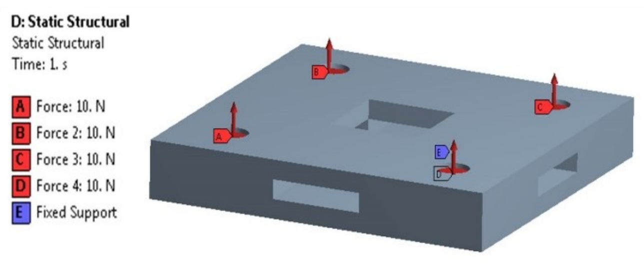

Fig. 4. Initial conditions: unibody quadcopter [15].

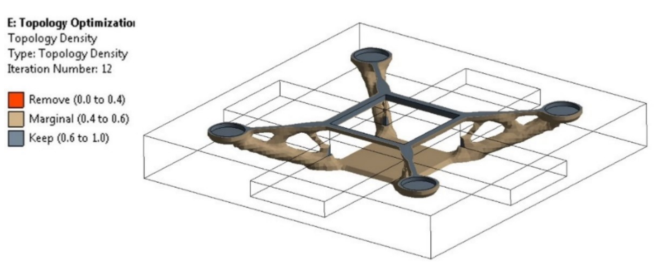

Fig. 5. Topology optimisation: unibody quadcopter [15].

part was validated, and the test results are converted back into Ansys to optimise the design with a focus on increasing the flight time and carrying capacity.

B. Fusion360 – Shape Optimisation

Autodesk's Fusion 360 offers topology optimisation and generative design, which is combined with shape optimisation. This approach uses the SIMP method for topology optimisation, where mass and stiffness are used as objective functions [19]. It also presents a rapid simulation process run in the software environment or in the cloud. The following examples were effectively developed using Fusion360 optimisation option: safety-relevant components, such as suspension parts [21], brake callipers [22] and steering knuckles [23], and also the complete chassis of an electric motorcycle [24].

The more detailed example is the lower suspension control arm [21], the most important component of the suspension system. This part is responsible for preventing the wheels from lifting off the body. Following the example, Biglete et al. [21] optimise the control arm of a Toyota Vios with the goal of reducing weight and volume. Therefore, three aspects are considered in the initial finite element method, namely the meshing, boundary and load conditions. This design is examined under two conditions: triggered jump and non-triggered. Through several tests, the maximum allowable deformation and stress were determined based on the initial part. Topology optimisation was successfully used to determine the critical load paths with a mass ratio of 85%. In addition, the applied force and fastening positions were selected as in the preserved areas. Based on the results, four different designs are identified and conducted with the finite element method focusing on total deformation, operational stress, and safety factor. One of the major objectives formulated in [21] is the weight reduction. However, the object structural strength is also considered a very important aim which has to be ensured. A comparison of the simulation results is provided with the focus of finding the best solution.

C. Solidworks - Simulation

Solidworks Simulation from Dassault Systémes offers size, parameter shape, and topology optimisation. Topology optimisation in Solidworks uses the compliance-based approach in combination with the SIMP method, where mass, stiffness, and displacement can be selected as objective functions [25]. Solidworks Simulation serves as a standard tool widely used at the design stage in many various industries. In the aerospace industry, for example, Leon et al. [26] successfully applied it to design quadcopters airframes, whereas Khan et al. used Solidworks to develop landing gear struts [27]. Furthermore, a Kuka KR16 robot [28] was redesigned using topology optimisation in order to increase productivity and accuracy. In addition, an example of topology optimisation in the medical industry is the development of foot prosthesis implants [29].

Leon et al. [26] applied topology optimisation by Solidworks to the design of the main structures of a quadcopter airframe. Their work was similar to the previously discussed study by Nvss et al. [15], except for the material selection procedure, which was conducted using additional software. Fig. 6 shows the stages of methodical implementation of topology optimisation executed by Solidworks. As the dimensions of the original airframe were quite large, a symmetrical design approach was implemented. As shown in Fig. 6a, the design provides an area for electronic component installation and four positions reserved for the propellers in the airframe body.

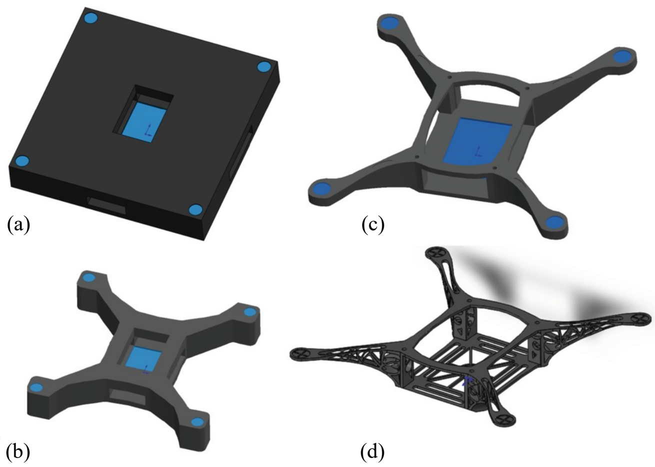

Fig. 6. UAV airframe topology optimisation: (a) initial design; (b) 2nd iteration; (c) 3rd iteration; (d) optimised design [26].

The assumption was made that each propeller produces a thrust force of 30N. Solidworks topology optimisation was used to generate the first approximation of the optimal design based on the defined boundary conditions (Fig. 6b and Fig. 6c). After several iterations, the airframe design was optimised in accordance to weight and strength criterion using the SIMP method (Fig. 6d). It was observed that after the topology optimisation process, the entire drone system was redesigned and afterwards examined in accordance with the payload capacity applied as the primary design goal. Examination revealed that the total weight of the drone components should not exceed 2kg, and the body of the drone should weigh less than 0.4kg to achieve the desired payload capacity. The determined safety factor reflects that the design can endure a load weight of approximately 21.2kg.

D. nTopology – Simulation

nTopology is a stand-alone software offering size, parameter, shape and topology optimisation as well as further lattice topology optimisation (LTO). As an optimisation algorithm, nTopology uses the SIMP method, which simultaneously considers complex, multivariate loading conditions and design constraints. These include the volume fraction of the original design space, the compliance under certain loading conditions, or the amount of stress or displacement. Lattice topology optimisation, as an advanced method, provides optimal technical or architectural structures that make the object lighter, but also stronger. As shown in Fig. 7, this type of structure uses different crosswise arranged patterns [30],[31].

nTopology tool is relatively new and extremely advanced software released in 2015. This is why there is a luck of relevant publications available in order to compare it to the other optimisation programs. However, there are some examples of implementation of LTO, core optimisation algorithm for nTopology. For example, in medical technology lattice structure geometries are used in the development of orthopaedic hip implants [32],[33]. Izri et al. [32] deal with the development of patient-oriented hip implants by changing the design through LTO under an

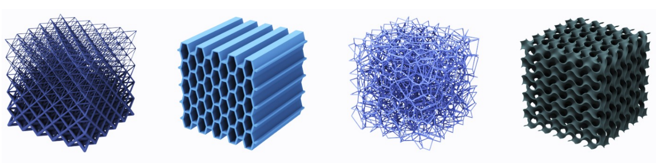

Fig. 7. Lattice structure types [31].

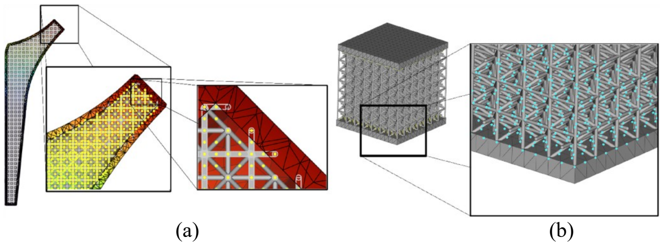

Fig. 8. Rigid shell and infill lattice design: (a) hip implant; (b) cube structure [32].

analytical study of different materials. Comparing to conventional implants, the lattice structures ensure reduction in the implant mass and stress wear. The researchers compare various lattice structures and how they behave when a force of is applied over the hip joint position. The optimised design, seen in Fig. 8, is evaluated by changing beam-based lattices and material into Ti-6Al-4V, TA15 and CoCr28Mo.

After a comparison of the simulation results with several lattice structures, it has been concluded that under different structure thickness conditions, the Weaire-Phelan lattice performs better than other structures. Further, the structure offers the highest efficiency in relation to the lowest weight, and the maximum reduced stress.

IV. Discussion

Data from 14 different research reports used the topology optimisation software (Table I) are summarised and evaluated. It should be noted that it is not apparent whether the researchers have access to a full commercial application, the only information available is in which year the experiments were conducted and therefore one can infer the version of each software. In the summary (Table II), the topological approach, the meshing, the investigation type, the percentage weight reduction and finally the industrial area are documented and analysed. Comparing all industry sectors of the referenced topology optimisation, it becomes apparent that almost all of them can be divided into the aerospace, automotive and medical sectors. Only the Kuka KR16 robot project [28] cannot be specified, nevertheless, it is also used in the areas mentioned. It is therefore hardly surprising that the three industries benefit from topology optimisation. Given the central importance of weight reduction issues in the aerospace sector, it is hard to imagine this industry without topology optimisation. It is intensively used for the design optimisation of structural components of the airframe, but also for safety-relevant components [16],[17],[27]. A growing sector in this area is the development of UAVs [15],[26], where the ratio between maximum stiffness and maximum weight reduction significantly affects the flight operations. In automotive design, topology optimisation can be applied to integrate the lightweight design needed for fuel efficiency and vehicle performance with the stability and strength that geometry must have to withstand drive forces and impact [24]. However, topology optimisation can contribute not only to material or weight savings but also to improving safety components for occupants [18],[21]-[23]. Topology optimisation also proves ideal for implantation design in the medical industry, as they give developers of medical applications complete freedom in the design of shapes and surfaces [29],[32],[33]

With a numerically generated examination, errors can occur due to the software itself, but also due to the user implementation. For example, a wrongly chosen or inaccurate meshing can lead to wrong results. Comparing the papers among each other, it can be seen that most of

TABLE II. EVALUATION OF COMPUTER-AIDED TOPOLOGY OPTIMISATION SOFTWARE.

Author		Conducted	Software	Method/Function	Mesh/Elements	Investigation	Weight Reduction	Industry
Nvss et al.	[15]	2022	Ansys Mechanical	SIMP/ Compliance, Mass	Tetrahedral 424.430 elem.	Numerical/ Experimental	96%	Aerospace
Hub et al.	[16]	2019	Ansys Mechanical	SIMP/ Compliance, Mass	-	Numerical	31%	Aerospace
Pappalardo et al.	[17]	2021	Ansys Mechanical	SIMP/ Compliance, Mass	Tetrahedral 10.791 elem.	Numerical	16,67%	Aerospace
Zeng et al.	[18]	2022	Ansys Mechanical	SIMP/ Compliance, Mass	-	Numerical	19,2%	Automotive
Biglete et al.	[21]	2020	Fusion360	SIMP/ Compliance, Mass	-	Numerical	5%	Automotive
Sharma et al.	[22]	2022	Fusion360	SIMP/ Compliance, Mass	-	Numerical	30%	Automotive
Petr et al.	[23]	2020	Fusion360	SIMP/ Compliance, Mass	Tetrahedral	Numerical	60%	Automotive
Ahmad et al.	[24]	2021	Fusion360	SIMP/ Compliance, Mass	Hexahedron 34.471 elem.	Numerical	80%	Automotive
Leon et al.	[26]	2021	Solidworks	SIMP/ Compliance, Mass	-	Numerical	62%	Aerospace
Khan et al.	[27]	2021	Solidworks	SIMP/ Compliance, Mass	-	Numerical	60%	Aerospace
Lakshmi et al.	[28]	2021	Solidworks	SIMP/ Compliance, Volume	-	Numerical	70%	-
Fey et al.	[29]	2022	Solidworks	SIMP/ Compliance, Mass	-	Numerical/ Experimental	35%	Medical
Izri et al.	[32]	2022	nTopology	SIMP, LTO/ Compliance, Mass	Tetrahedral	Numerical	57%	Medical
Kladovasilakis et al.	[33]	2015	nTopology	SIMP, LTO/ Compliance, Mass	Hexahedral, Tetrahedral	Numerical	38%	Medical

them only mentioned the type of mesh elements and not the amount of the elements. Only three papers provide an element count including [15] which shows a good meshing having approximately 2 million elements. Therefore, it is essential to validate the results and verify it experimentally − this approach is implemented only in 2 projects. Nvss at al. [15] manufactured the quadcopter airframe and compared it with the numerical simulation results. However, it was noticed that even in an optimally prepared simulation, the differences between numerical modelling and tests can occur. It provides an opportunity to go back to the simulation after testing and using validated values, adjust the design and optimise it for further testing.

The analysis in terms of weight reduction percentage shows that each software related to test case demonstrates weight reduction in comparison to the initial design. It is noticed that the converged design must be re-designed after post-processing since the SIMP method is a density-based method, it is not focused on manufacturability [6],[34]. Ansys and nTopology, for example, offer the LSF approach which considers the boundary surfaces of the generated geometry separately. As a result, the structure is smoother, even without additional rework, and a more uniform stress distribution is achieved. However, Solidworks and Fusion do not offer this approach, which requires a subsequent adaptation afterwards. Nevertheless, topologically optimised structures are usually characterised by a complex geometric configuration. It makes difficult to fabricate these generated structures using traditional manufacturing techniques and requires additive manufacturing such as 3D printing.

Overall, all programs have their advantages and disadvantages. In general, Solidworks and Fusion360 are better suited for non-complex topology optimisation due to their limited features compared to the others. However, the decisive advantage is that even the student version offers all features [19],[25]. Although Fusion360 is being developed to implement an lattice structure application suitable for analysis, the current function provides only visual customisation for additive manufacturing but not for functionality. Due to extended functionality and a large number of optimisation options, Ansys and nTopology are considered more advanced compared to the other software. Ansys advances with capabilities in computational fluid dynamic simulation which none of the other programs can offer. It also gives the possibility to carry out lattice topology optimisations and simulate them afterwards. Unfortunately, the student version of Ansys has some limitations. Although all functions are included in the student version, the meshing is limited to only 512,000 elements in CFD and 32,000 elements for structural analysis. Ansys, Fusion360, Solidworks are CAD and CFD programmes in which topology optimisation is integrated. In contrast, nTopology is a kind of an engineering tool and can be compared to a programming language that is perfectly suited for design rather than design software. The integrated simulation tools focus on design analysis, the results of which can then be used as input for part geometry. The advanced geometry core, based on the implicit modelling method, produces strong geometries. Most conventional programs, i.e. Ansys, Fusion and Solidworks with integrated topology optimisation, outperform nTopology in terms of acceptability but also provide the same level of performance in terms of implicit modelling or mesh generation. Probably the biggest drawback to nTopology is that it is not popular enough across engineering community and still needs to find its place in existing design workflows.

V. Conclusion

This paper provides an overview and explanation of the general algorithm of topology optimisation and how it is implemented in today's topology optimisation software. Four topology optimisation software were selected for detailed examination. These are the integrated applications of Ansys, Fusion360 and Solidworks, and the stand-alone software nTopology. The analysis focused on the software parameters such as availability, optimisation methods, objective functions, meshing, research implementation, weight reduction and their industrial areas. The individual capabilities of each program are examined and their advantages and disadvantages are analysed. The similarity of all the topology optimisation software studied is generally very beneficial to the engineering community, and they are capable of optimisation a wide range of applications. However, each software has its own capabilities and limitations that distinguish it from the others and it must be carefully selected depending on the industry and application area.

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