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Generative Design and Topology Optimisation of Products for Additive Manufacturing

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Abstract. The aim of this paper is to assess the impacts of topology optimisation and generative design on design optimisation processes when paired with additive manufacturing. This is being done as topology optimisation is a common practice in industry, but the advent of generative design may allow for further critical refinement of parts while maintaining functionality. Additionally, when paired with additive manufacturing the benefits of generative design compound with material savings and the ability to maximise the effectiveness of generative designs complex, organic geometries. A car suspension upright was manually created as an original design. The process of topology optimisation was undertaken on the original part, and a volume reduction to the original part of 65.17% was achieved. Using a case of loading of turning braking, a generative design was produced. This achieved a volume reduction of 88.13% when compared to the original design and 65.91% when compared to the topology optimisation result. Prototype parts were then produced in ABS via the FDM additive manufacturing method as a proof of concept. The optimisation processes on the design were both successful with the topology approach providing a stronger part while the generative design provided a bespoke, refined design using much less material of organic nature. It is found that the generative methodology also provides significant positive sustainability impacts.

Keywords. Additive manufacturing, generative design, topology optimisation.

1. Introduction

Topology optimisation is often used with additive manufacturing (AM) as the nature of the manufacturing method allows for the complexities of the optimisation to be enacted. Additive manufacturing uses a layer by layer approach allowing complex 3D structures to be manufactured with reduced production times [1]. The nature of the layer by layer addition of material, in contrast to the traditional subtractive manufacturing methods, allows for rapid prototyping of designs at a high quality, lower cost and much reduced waste of material, especially for complex shapes that need manufacturing [2]. However, there are some issues with using AM with topology optimisation. AM can struggle and fail with certain structures such as enclosed voids and overhangs, and in terms of topology optimisation there can be issues with the design. As topology optimisation uses a discretisation method with the meshing in the software, leading to the final design being dependent on the mesh quality used in the process so could be suboptimal if there are

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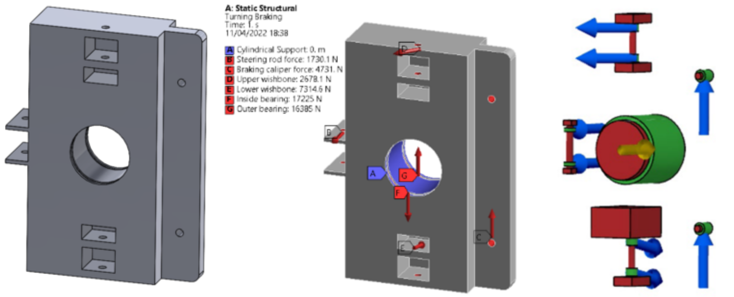
meshing issues and a checkerboarding issue [3]. The checkerboarding issue is defined as the formation of alternating regions of solid and void material elements in the mesh, in a post-processing to eliminate the checkerboarding, using a higher order of finite elements, patching the checkerboarding or filtering in post-processing to reduce the impact of the issue [4]. Another issue linked with topology optimisation with additive manufacturing is overhangs with AM. As the topology optimisation process does not account for the limitations of AM and can result in overhang structures that the manufacturing method cannot meet. Downward facing surfaces are an issue with AM and must not come below a critical value with respect to the baseplate [5]. Research has found the usual critical value to be 45 degrees and as topology optimisation does not account for this if a design has a feature breaching this the design must be constrained and reiterated to remove the issue as it is unprintable. This is achieved via altering the geometry to remove this issue or adding support structures during printing, but with large products or large scale manufacturing this will lead to a dramatic increase in cost and wastage which negatively impacts sustainability and should be sought to be avoided. Topology optimisation does not require design variables to be considered in the process but instead focuses on the structural problem, objective function and state variables definitions [6] to alter the geometry of the part. In ANSYS, the objective function being used is the aim to minimise compliance in the part which translates to maximising the stiffness of the structure making it as strong as possible under constraints. The structural side takes into account the material's properties and forces acting on the part. The state variables cover the restrained variable that the objective function must comply with which may be volume constraints for material distribution which can be used to give the aimed volume reduction to reduce weight. This is the driving constraint that the objective function is seeking to meet most efficiently. Generative design is a design practice that uses an algorithm and parametric modelling to quickly explore several design possibilities or design optimisations which leads to designs that look organic and representative of what we would see in the natural world [7]. Generative design is achieved by taking initial design inputs where the constraining points are created in software, this is not an initial model of the part just key fixed points. These are places in the design that are predefined and must be there and left untouched from the initial inputs. This could take the form of bolt holes or fixing positions on a part. Then on these constraints, a loading case is used to define the forces acting on each initial design point to give the program the information it needs to assess the material distribution and material paths. Additionally, obstacle geometry can be added to tell the program areas it cannot build in and must avoid putting material in. The program is then to create iterations of designs based on an objective and constraint which take the same form as topology optimisations equivalents as previously discussed [8].

This paper will investigate the parts generated through topology optimisation and generative design, to understand the limitations of each method paired with additive manufacturing. This research is valuable as generative design is a major emerging technology with potentially massive applications, while topology optimisation is already a staple. This research allows the comparison between the two methods with an examination the methods side by side to see how the application of generative design compares to what is currently being done. There is limited research in this area and the application of this method with additive manufacturing unlocks its full potential due to the new and evolving nature of generative design.

2. Methods

To start the study into topology optimisation and generative design, an original design of a car suspension upright was generated in SolidWorks. This was done without using a specific dimension as the part is to be used as a canvas to produce materials to demonstrate the use of topology optimisation and generative design. The part is shown in Figure 1a. This initial design was then transferred into ANSYS where load constraints were set up on the part as shown in Figure 1b. The loading cases have been sourced from a paper on upright design for formula cars [9]. The loading case of turning braking is used for the part. The material used for the original design was aluminium 2024 T6 which can be used for additive manufacturing methods such as powder bed fusion.



(a) (b) (c)

Figure 1. a) Initial design geometry b) Set up of load constraints c) Constraint and Fusion 360 design set up

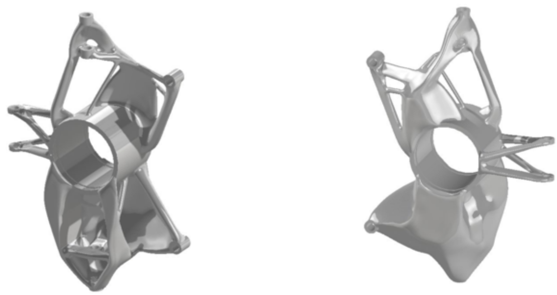
Topology optimisation on the original design was conducted under the turning braking load case and running it through ANSYS' topology optimisation function. This was achieved by selecting the whole body as the design region with the exclusion of any fixing points and the powertrain hole and bearing positions to keep these as designed. An objective function of minimising compliance was used with a varying constraining factor of mass retention. Several iterations were conducted with the aim of retaining 50%, 35%, 33% and 30% of the mass with the final selection of 33% mass retention being used for the manual redesign stage. For the generative design, the constraining geometries of the bolt holes and the centre hole for bearings and power train were isolated in SolidWorks as separate bodies as seen in Figure 3. These were then imported into Fusion 360 where the load case was established as seen previously with the turning braking state for forces, and additional obstacle geometries to stop material distribution where external parts would be or space was needed for fixing these parts were added. Figure 1c displays this methodology with the green sections being necessary geometry, arrows representing forces on the part and finally red sections being where material can't be distributed. Mesh sizes were checked for the finite element modelling.

3. Results

The topology density for 33% mass retention can be seen below in Figure 2a. A manual redesign was conducted in SolidWorks by overlaying the topology density profile over the original design (Figure 2b), and then manually removing material to shape the design closer to the optimisation result for manufacturing (Figure 2c). After the Fusion 360 model was run successfully using the additive manufacturing constraint with the aim of minimal mass and the minimum factor of safety of 5 across the part to allow it to withstand other load cases, a design as shown in Figures 3a and b was selected from the outputs. Compared to the original design, Table 1 shows volume reductions by topology optimisation and generative design.

(a) (b) (c)

Figure 2 a) Density profile front and back b) density profile over the original design c) optimised part

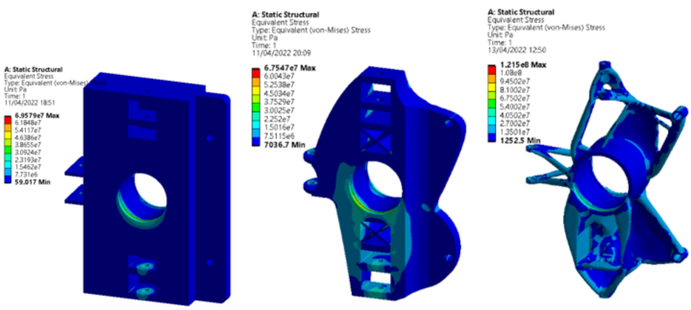


(a) (b)

Figure 3: Generative design a) front view, and b) back view

Table 1. Volumes and percentage reductions

Design	Volume (mm^3)	Percentage reduction from the original design	Percentage reduction from topology optimised design
Original	3981398.17	-	-
Topology Optimisation	1386704.46	65.17 %	-
Generative Design	472733.89	88.13 %	65.91 %



(a) (b) (c)

Figure 4. Von Mises stress at turning braking load, a) original design, b) Topology optimised design, c) Generative designed part

(a) (b) (c)

Figure 5. a) Original design b) Topology optimised design c) Generative design

The original design, topology optimised design and generative designed part are analysed in ANSYS under turning braking load. Von Mises stress plots are shown in Figure 4. The modelling was conducted with Ansys mechanical, using program generated element order and an element sizing of 2mm. This element sizing was selected as it provided a dense mesh profile over the surface of the models to accurately capture deformations and stresses. The model validity was assessed by visual inspection of stress concentrators being at expected locations and using deformations. This was done using the value of deformation and by applying a larger scale to visually inspect the direction and sizes of deformations and these inspections showed results we would expect. Using the FDM method, the parts were 3D printed in ABS to demonstrate the manufacturing applications of the design principles used. The printed parts are shown in Figure 5.

4. Discussions and conclusion

The values in Table 1 show massive reductions when in the realm of generative design. Looking at the stress results in Figure 4, it can be seen that no part fails under the loading case. Examining Figure 4, the stress profiles further highlight differences between the methodologies. The topology optimisation result has undergone a manual redesign and the strength this inherently adds can be seen with maximum stress experienced being 67.5 MPa. If we examine the generative design, we can see a maximum value of 121.5 MPa. This is a useful comparison as it shows how the software approach of the generative design is more efficient. This is as the software used for generative design optimises the material distribution most efficiently so while the stress seen is higher, this is better optimised for the loading case and material used, allowing less material to be used while it experiences higher stresses. The manual redesign phase of the topology design limits this benefit as it is done by a human and as such the optimal structure set up and material distribution isn't used. This highlights a key benefit of using generative design as opposed to topology optimisation in that it is a more efficient way to calculate material distribution for material savings, which is a key benefit when pairing with additive manufacturing with the organic structures generated.

The point of production costs is also impacted by the manufacturing method of additive manufacturing. This is because the manufacturing method reduces man hours to manufacture, the number of processes required and time, while saving material costs due to the additive, not subtractive method which further reduces costs. This is the key point of the research as the less volume in the part is, the quicker and cheaper it will be to produce which could be scaled up to an industrial standard once the manufacturing machinery is more widely available for mass consumer production. Both the topology optimisation and generative designs save volume compared to the original design with reductions of 65.17% and 88.13% respectively. Furthermore, the generative saves 65.91% of the volume of the topology result highlighting just how much material and as such time this design process saves. The application of these processes can be limited by two main factors, however. The most desirable method for additive manufacturing is generative design as its material savings are by far the biggest as seen in the results and as such outline a roadmap for future design applications to save materials, costs and time. It allows strong, natural looking structures to be generated which can be further refined to meet design requirements. Further refinement in particular utilises another way to achieve greater strength to make the part withstand all loading cases. This would be that of identification of key structural elements via further research. Key structural elements could be added in the initial preserve geometry stage to add features to the part the design must keep which could hardwire certain elements into the design once they were identified.

Both methodologies produce big savings on material, time and cost when paired with additive manufacturing. However, in the remit of additive manufacturing generative design is the ideal pairing. This is because generative designs of organic and complex geometries can best be met with additive manufacturing allowing a wider range of applications and structures to meet requirements while also saving a lot of material when compared to topology optimised designs. This is mostly due to the generative lack of an original design allowing much more free form constructions to organically meet a constraint while topology optimisation is much better suited to the refinement of an original manually designed part. This leaves generative design at the forefront of research into the design due to the much less constrained nature of design allowing a part much more freedom to naturally achieve its optimal design once the proper constraints have been applied.

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