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Integrating generative design and topology optimisation with product design values

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Abstract

Advances in computer technology and software increasingly encourage the usage of CAD tools for designing forms that algorithmically manipulate 'structural' and 'surface' features. These sophisticated new computational processes, broadly known as 'generative design' and 'topology optimisation', are very likely to become a regular part of the product design process for many types of products. A core value of design practice is the development of intuition and iterative skills to explore the technical and experiential performance of design concepts through sketching, model making, and prototyping. Identifying ways to integrate 'generative design' and 'topology optimisation' CAD processes with 'making' as a core value in product design concept development is a significant challenge - particularly for design education. A related concern is that 'topology optimisation' can generate structurally optimised parts for the amount and type of material used, which essentially determines the fabrication method. Often these parts in their raw form can only be made using 3D printing technologies, though they can (and often need to) be 'styled' or modified. Therefore, the relationship to 3D printing and its limitations as an end-part manufacturing technology must be critically tested as part of the design process. The practice-led research presented includes a case study of the design of a mountain bike (MTB) crank arm developed using an integrated design process that incorporates a series of 'topology optimisation' simulations. The authors undertook the project to inform the design of a new 'generative design' and 'topology optimisation' studio-based subject to be offered to second and third-year product design students at the University of Technology Sydney. The research proposes a form of integrated design practice that values 'making' iteratively, and the advancing CAD-based 'generative design' and 'topology optimisation' tools to responsibly support experiential learning in product design, manufacturing and engineering.

Keywords

Product design education; CAD; Generative Design; Topology Optimisation

Introduction

We refer to terminology in this paper that ought to be understood before we present the research conducted in this project:

Generative Design: Generative Design (GD) is a process of simulating multiple design alternatives simultaneously that comply with conditions set by the designer. Computational GD gives the designer control over the conditions and their values, enabling exploration of many design permutations beyond human capacity and perhaps more effectively arriving at a preferred design variant. While generative processes are not limited to the field of design, the benefit of this process for product designers is the opportunity to synthesise three-dimensional forms via a process of growth occurring because of load conditions set by the designer.

Topology Optimisation: Topology Optimisation (TO) is a structural optimisation process to minimise the use of material but maximise the stiffness of a part within its prescribed boundary. When a computational approach is initiated, the designer must first create a load case (setting the force magnitude and position in three-dimensional space). TO can then computationally remove material within the set boundary conditions, which will change the shape of the resultant design. The designer can adjust the conditions over time and rerun the simulation to produce another iterative instance moving closer to the performance requirements of the design.

MTB Crank Arm: Mountain Bike ('MTB' abbreviated) Crank Arm

This paper looks to the future of design education and design practice. Product design programs must implement emerging practices carefully in ways that respect a theoretical framework but allow space for skill development with software tools in constant flux. Shea, Aish and Gourtovaia considered that the computer's role could be as a "collaborative partner" in "stimulating solutions …to...rigorous models of design conditions" (2005, p.253). But how can we synthesise and implement the emergent tools in the landscape of computational design to augment the arsenal of tools and methods product designers currently use? How will this affect the education of undergraduates and the practice of graduates? It is the answers to these questions that we will explore in this paper, focusing on themes of Generative Design and Topological Optimisation.

Literature review

In the landscape of Computational Design, Generative Design (GD) exists as a process methodology within it (see Figure 1). Topology Optimisation resides within that same landscape of computational design. Still, it exists as a process that overlaps with Generative Design because of the nature of algorithmic manipulation of geometry. The main distinction is that Topology Optimisation deals with a singular three-dimensional geometric solution to a structural efficiency query. Generative Design is more far-reaching as it can be employed as a process to generate multiple concepts in any field (including geometric solutions) where humans apply their creativity, with the potential to produce concepts in infinite variety.

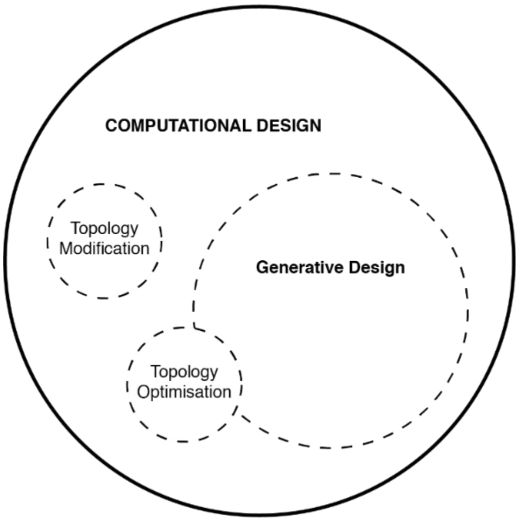

Figure 1. Computational Design opportunities

"Generative design produces events that are unique and complex. Uniqueness and complexity are strongly related to each other" (Soddu, 2002). Generative systems can be helpful in "sparking new design ideas ... solving difficult tasks …(which) extend designers' current capabilities" (Shea, Aish and Gourtovaia, 2005). Some applications for GD can be in producing concepts for two/three-dimensional geometry (such as in architecture and product design) or the production of artwork, or the composition of music and prose. As Soddu (2002) explains, "generative code functions as DNA does in nature, it uses artificial life to generate a multiplicity of artworks, artificial events, architectures and virtual environments".

To establish the parameters to incorporate Generative Design processes into product design education, we must first attempt to define the terminology adequately. "Many people take the view that Generative Design is something of a generic term for using computation in the design process" (Altair, 2019). The definition of Generative Design has seen subtle shifts over the past decade, and one might expect that the process must involve software-generated outcomes, but this is not strictly the case. A Generative Design process could be employed to generate concepts without using computer software. Project work in design schools typically unfolds with multiple students in undergraduate year groups undertaking the same project brief under similar conditions. In this situation, the students are the 'generators' of designs, and the studio leaders impose conditions through feedback. The advance in computing power and more sophisticated software tools have created the opportunity for more efficient processes. Arguably now, the software tools (see figure 8), training resources, and the computational power of typical laptop computers make it a reality for students to explore in the studio environment. Looking to the recent past, Chase (2005) stated, "Design is complex. Consequently, the development of design automation tools has been slow", but now one might say that the simulation tools have matured to offer efficient usage and structural insights for novice designers.

Then what is Generative Design? The most important role it can play is encouraging "greater exploration of possibilities" within a set of parameters (Schumacher & Krish, 2010). Search queries conducted for 'Generative design' reveal various weird and wonderful three-dimensional forms potentially created by software-driven form generation processes. The most easily recognisable feature that GD provides is the opportunity to develop "exuberant forms" (Schumacher & Krish, 2010).

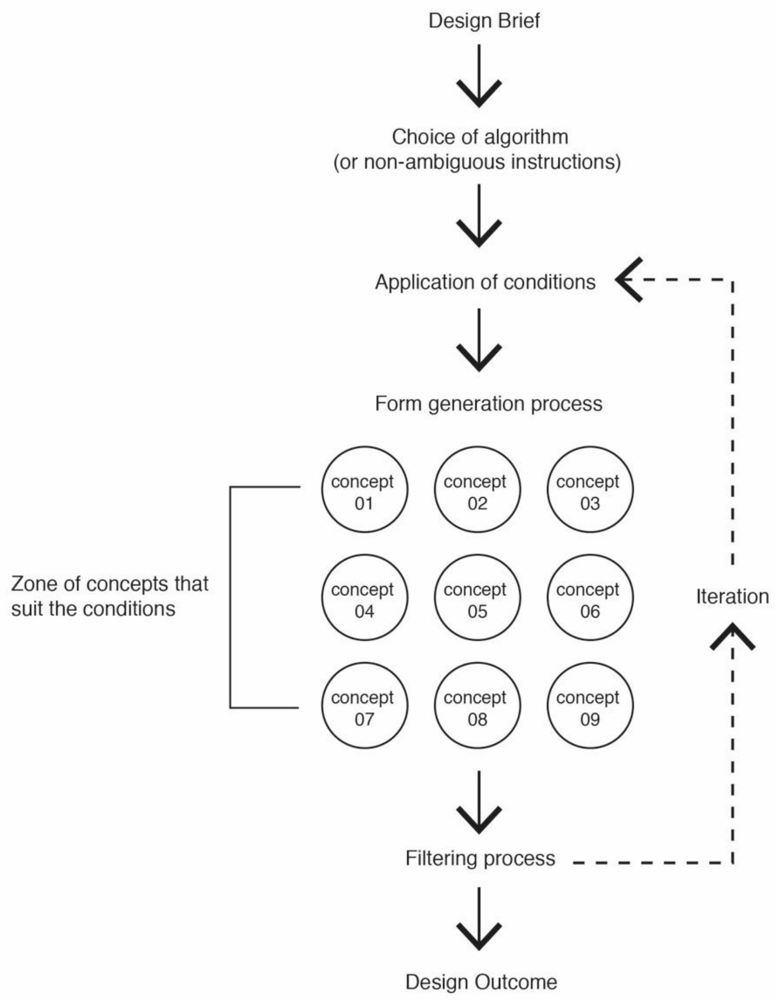

Figure 2. Diagram of a Generative Design process

To explain this in simple terms, GD provides the opportunity to "generate and explore (a multitude of) alternative design proposals" and also to "analyse and evaluate them" (Janssen, Frazer & Tang, 2002). Arguably, it now resides at the heart of computational design. Figure 2 describes a Generative Design workflow in a streamlined way. The approach has been abstracted and is possible without computer software tools. Once a project brief has been established, an algorithm (non-ambiguous set of instructions) is selected. Then, conditions (variables) are put in place to generate a range of concepts within a zone defined by the limits of those variables. A filtering process then narrows the field. Further iteration may be required to advance the process toward a suitable design outcome.

There is a wealth of literature on GD for developing architectural concepts. This literature focuses on computer usage as a solving tool with either off the shelf or bespoke (specially written for the task) software. The advance in thinking in this realm has led to the employment of various solver algorithms. The move towards more 'active' and sophisticated software tools allows a shift in design process methodology where the tools themselves can be "relocated at the centre of the design process" (Janssen, Frazer & Tang, 2002). In an explanation of GD, these algorithms need to be mentioned, and some in everyday use are 'L-systems', 'shape grammars', 'cellular automata', 'genetic algorithms' and 'swarm intelligence' (Singh, 2011). A detailed explanation of these algorithmic types is beyond the scope of this paper.

In the commercial version of Autodesk Fusion 360, a recent but sophisticated system, the incorporated Generative Design module can generate the three-dimensional form of a part given a set of geometric and force parameters (figure 3). The resulting shape of the part is not known at the genesis of the software simulation, and the system allows a designer to guide the process by filtering the results.

Figure 3. A violin bridge (Petit, 2008)

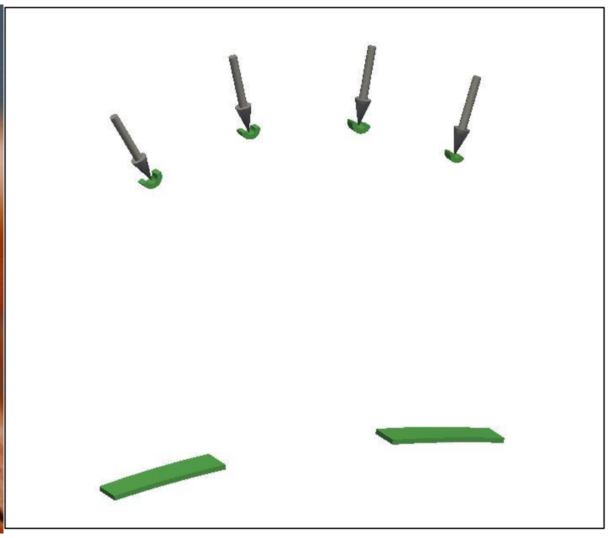

Figure 4. Setup of geometric and load constraints in Autodesk Fusion 360 (Perry, 2018)

A hobby project conducted by David Perry (2018) used Autodesk Fusion 360 Generative Design tools to produce concepts for a violin bridge[1]. Figure 3 is an image of a traditional timber violin bridge. Figure 4 displays the geometric and force conditions from which the software produced multiple alternatives. Figure 5 depicts the array of results that fit those conditions. Figure 6 is the chosen form to be made by additive manufacturing (AM). Considering the exuberance of the structures shown in figure 5, it stands to reason that they are more suited for production by additive rather than subtractive manufacturing methods.

Interestingly, Autodesk Fusion 360 provides an opportunity to apply various manufacturing constraints to the form generation process, influencing and making the output manufacturable. In economic terms, it has been established that “AM technologies remain best suited to small-batch, custom and niche applications in aerospace, medical and automotive industries” (The Economist, 2019). Coupling Generative Design with AM to realise complex forms empowers both technologies, particularly when this creates a high-performance design with a complex and appealing aesthetic quality

[1] Traditionally, a timber load-bearing object supporting the strings capable of transferring vibration to the surface of the instrument body.

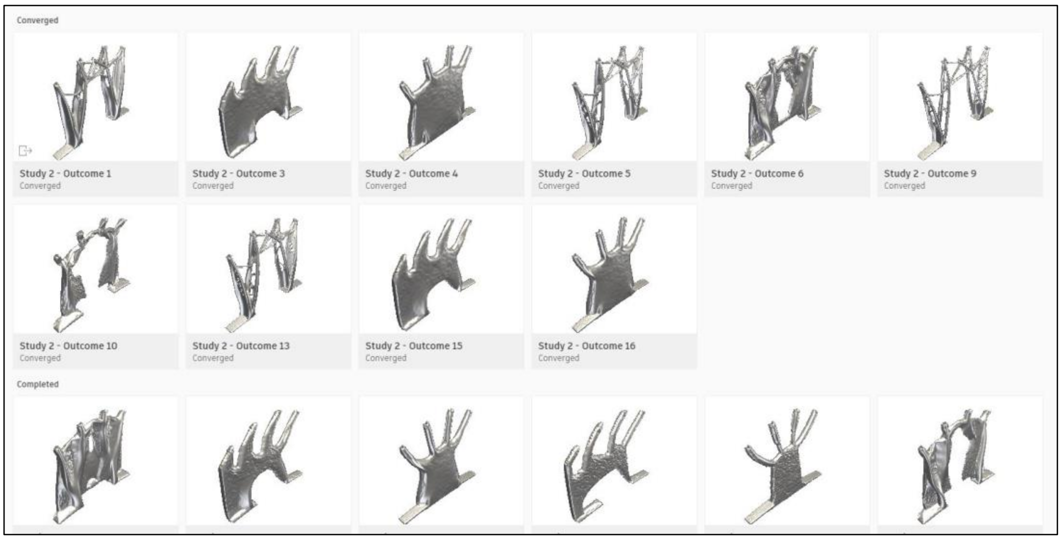

Figure 5. Array of results of the generative process inside Autodesk Fusion 360 (Perry, 2018).

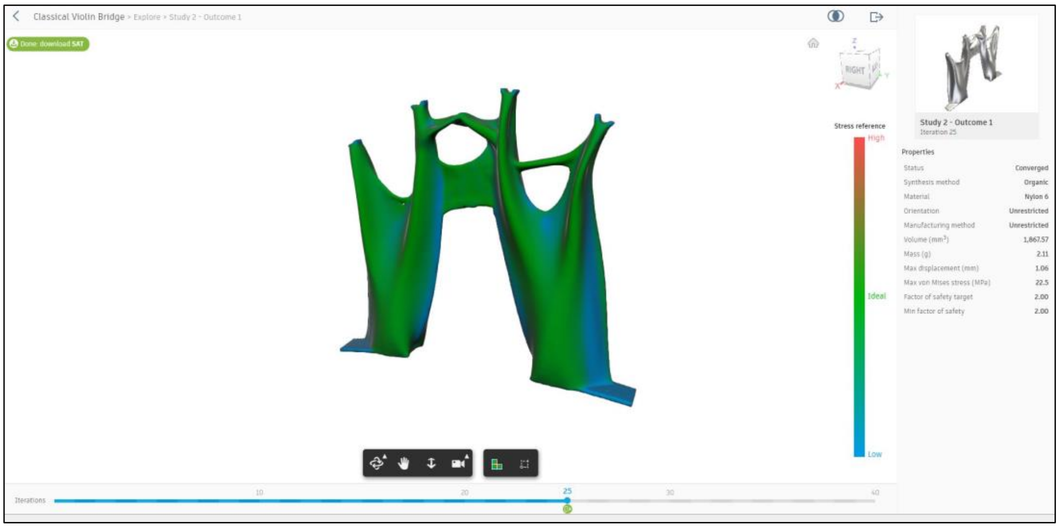

Figure 6. The chosen design (Perry 2018).

Topology Optimisation

Altair produced the first commercial Topology Optimisation software product 'Optistruct' in the 90s. With the advances in additive manufacturing technology, objects created through digital Topological Optimisation processes (sometimes called 'shape optimisation', 'structural optimisation' or 'light-weighting') can be easily manufactured. In the recent past, Topology Optimisation has been restricted to high-performance industries such as aerospace and automotive situations where any given reduction in material weight has led to substantial cost benefits. Figure 7 explains the pathway through a Topological Optimisation process where the shape envelope and performance characteristics of a part are already known. This is a restricted design exercise solved by an algorithm that typically removes material volume from a three-dimensional CAD model until a goal is reached (Altair, 2019). A common goal might be "to find the stiffest possible design using the least material" (Altair, 2019), but other efficiency goals are possible, like achieving thermal efficiency. Parameters set by the operator would dictate what percentage of the total mass is removed. We experiment with this process later in this paper to redesign an MTB crank arm.

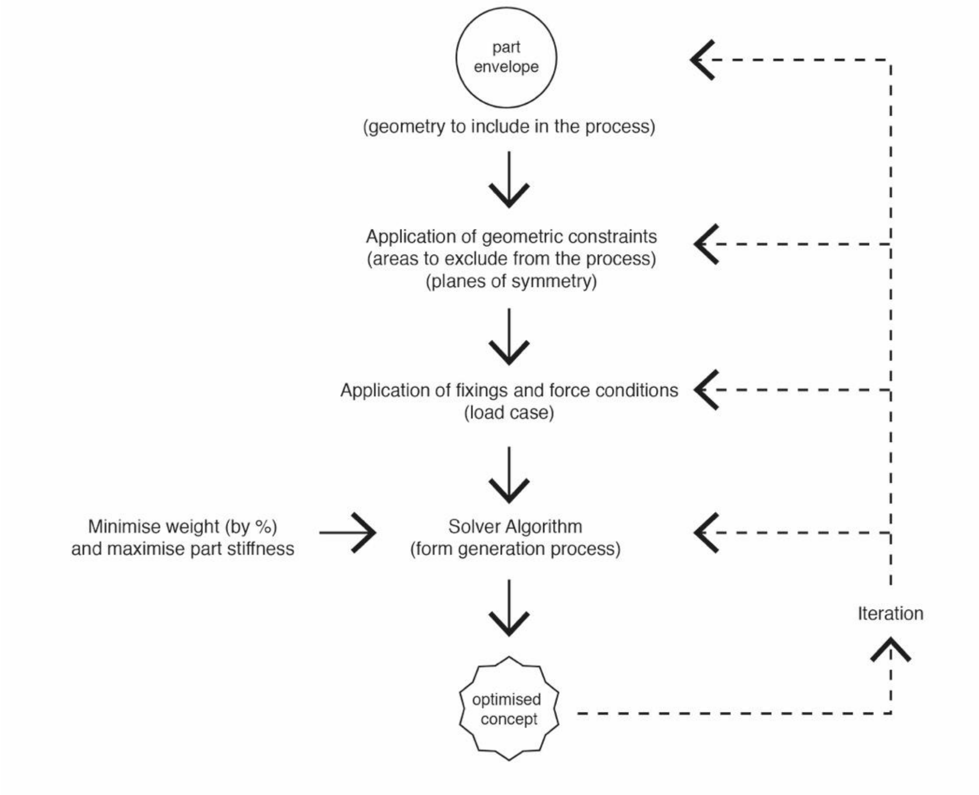

Figure 7. Diagram of a Topology Optimisation process

Topology Optimisation and lattice structures

The range of software tools available for Topological Optimisation processes is vast, and the predominant focus is that engineers are the end-users of this technology. This situation is not ideal for Product Design education. We have explored a range of tools suitable for Product Design education (see Figure 8).

Here, it is worth distinguishing between Topology Optimisation employed to achieve an efficiency goal (structural or thermal) versus Topology Manipulation, where removing material from a shape envelope might be only for aesthetic reasons, which is not an efficiency goal. The generation of lattice structures can fall into both categories. The primary benefit of lattice structures is that they sit well with the constraints of powder-based additive manufacturing processes to minimise material use and post-processing (powder removal) of components. Software tools such as nTopology and Materialise 3-Matic can generate and manipulate lattice structures with incredible variety based on FEA[2] data to optimise the structure. In figure 8, a range of software tools is presented with a subjective comment to describe their potential in product design education workflows. Via an exploration of these software tools in the formative research phase for this paper, the authors chose Autodesk Fusion 360 for the Topology Optimisation experiment to redesign an MTB crank arm. At the writing of this paper, Autodesk Fusion 360 is accessible and available for education users and is straightforward to use, along with offering practical online training resources. Solidworks is another good choice for Topology Optimisation processes.

[2] Finite Element Analysis (FEA) uses computer simulation to test the structural performance characteristics of a given part provided in the form of CAD data.

Software Tool	Commercial/Education	Usage Case
Altair Inspire	Commercial & Education	Topology Optimisation Sophisticated and straightforward for Topology Optimisation processes with a powerful polynurbs tool to build geometry over generated forms.
Autodesk Fusion 360	Commercial & Education	Parametric and Generative Form Generation/Topology Optimisation Sophisticated and straightforward for Topology Optimisation processes.
Autodesk Meshmixer	Commercial & Education	Topology Manipulation/Manipulation of polygonal models Can modify and thicken meshes, useful for aesthetic explorations.
Materialise 3-Matic	Commercial	Topology Optimisation/Manipulation Extensive tool set for AM applications including topology optimisation of lattice structure based on FEA data.
Autodesk NetFabb	Commercial & Education	Topology Manipulation Includes versatile tools for AM processes which includes generation of lattice structures.
nTopology Element	Commercial & Education	Topology Manipulation Generation and manipulation of lattice structures, more powerful in the commercial version.
Rhino + Grasshopper	Commercial & Education	Topology Optimisation/Manipulation Rhino is a powerful form generator with its abilities extended greatly by plugins like Grasshopper.
Solidworks	Commercial & Education	Parametric form generation/Topology Optimisation Solidworks is the industry standard for product design it is a powerful form generator with recently added shape optimisation tools.

Figure 8. Software tools for Topology Optimisation[3] beneficial for product design education.

Design process and education

Previous research identifies iteration as a base feature of the design process (Chuslip & Jin, 2006) and can be traced to the generation of diverse and creative ideas (Brophy, 2001; Liu, Bligh & Chakrabarti, 2003). Gotzsch (1999) has described the industrial design process as one that switches back and forth between functional, emotional and aesthetic features of a design. This switching may be the way learning through design iteration happens. The development of diverse ideas - divergent thinking - has value as a feature of formative and summative product design phases in design education (Nemme & Walden, 2016). Additionally, research by Yilmaz & Daly (2016) and Daly, Yilmaz, Christian, Seifert & Gonzalez (2012) indicate that concept generation in the mid-later stages should be supported, and the creation of multiple and diverse concepts can lead to successful innovation in design. Complex products that have to conform to existing platforms, such as how the creation of an MTB crank arm must balance size and fit standards with performance improvements, often force substantial constraints on concept design (see Pugh, 1991 and Wynn & Clarkson, 2005).

[3] Since the original research around testing of the software products was undertaken in 2018, the 'nTopology Platform' has matured and contains a full suite of tools capable of field-driven design and Topology Optimisation processes far beyond what was available in the 'Element' product it is now another contender for educational use.

Generative design and topology optimisation may expand concept design for these tightly constrained projects and, in doing so, encourage divergent thinking, iteration and innovation inside the design process. There is ongoing research investigating how additive manufacturing technologies and associated computer modelling software integrate with design practices in an organisational context. Linking these emerging technologies with design practice at first seems straightforward. Still, it can be difficult because of several factors, including the infinite ways the computer software can create a form to operate suitably for an application based on load-case data. In the early phase of a design process, generative design has been advocated to creatively explore potential design directions and uncover unanticipated ones (Krish, 2011). However, many design alternatives need to be interpreted for practical application and production feasibility in the final stage. Some guidelines are starting to emerge, such as pursuing bio-inspired geometries where 'bone-like' structures have achieved the lowest cost and impact on the environment (Zhang et al., 2018). The study suggests the need for a 'framework' by developing a 'structure library' to assist researchers and engineers (designers) in guiding additive manufacturing industrialisation to test designs and the limits of the technology.

Other research has identified that the smooth transition from conventional manufacturing 'thinking' to design for additive manufacturing ought to accommodate material optimisation and product sustainability issues. While generative and topology optimisation software is a 'synergetic' tool for this, they do not remove the need for 'manual interpretation of the results' (Gebisa & Lemu, 2017). Given what has been determined in other research, 'manual interpretation' can mean both the designer's intuition and experience to select (and modify) forms generated and, later, testing the resultant designs against performance criteria (e.g. strength and durability). In an educational context, it's important to manage 'fixation' against the values of 'iteration' (Nemme & Walden, 2016; see also Cross, 2007). The software used early in the process generates multiple alternatives, and design novices tend to converge on one solution early (see Schumacher & Krish, 2010).

Method

The research investigates how product design teaching and learning may integrate generative design and topology optimisation processes to advance the value of early-stage, iteration and practice-led enquiry. The project pilots an assessment task to be installed within a new product design elective developed at the University of Technology Sydney. The elective is set up to teach product design students generative design and topology optimisation as embedded components of the product design process. The research uses generative design and topology optimisation software to design a product. The method is mapped across existing models of design used in product design subjects within the UTS program to propose a way of synthesising iteration and practice-led enquiry values with these emerging computer-dependant processes of generating optimised forms.

Prototyping a subject based on a Topology Optimisation process requires a vehicle for learning. To extract the most benefit from the optimisation process, we decided that the component needs to be high performance, structural, of the correct scale and within a product category that suits our contextual knowledge. For these reasons, a mountain bike (MTB) crank arm was selected as the product to be designed. A product autopsy of an existing high performance, forged aluminium MTB crank arm (by a respected company specialising in bicycle components) was conducted, providing the basis for standard sizes, the position of structural connections, offsets required and an understanding of performance styling. Critical and overall dimensions gained from the product autopsy were used to create the 'genotype' – a computer-generated 'base' model that sets boundary conditions for any design variations occurring during the 'optimisation' process.

The topology optimisation software used is Autodesk Fusion 360. The research generates six design alternatives representative of possible design directions by manipulating several variables: envelope size, symmetry, force location/magnitude and mesh density[4]. The solver algorithm requires a mass reduction percentage to be entered (typically 30-40%), and it then removes material from the shape envelope while maintaining the maximum stiffness of the component. It should be noted that there are ways the model can be varied to generate alternatives and that within each of the resulting forms, there are many iterative possibilities via manipulation of the variables. Expanding beyond these variations to create interesting forms may have value as an exploratory exercise. However, since the product is an MTB crank arm, optimisation should first focus on mechanical performance (i.e. be strong and durable but also light-weight). We have specified ‘steel’ for each of these generative designs. Steel is heavier than the aluminium typically used for these products; however, we estimate that the optimisation procedure will remove enough material bulk to create a more durable steel crank arm with a similar performance to one made from solid aluminium (see Pandolfo & Walden, 2010).

After generating the alternative designs, we select one for further (stylistic) refinement to produce an exterior surface form that attempts to make the design more acceptable and appealing as a consumer product. Though it is beyond the scope of our research in this paper, the generative designs, given their complex forms, could be 3D printed in metal using several developing technologies: direct metal laser sintering, selective laser melting or electron beam melting (if made in titanium). It should be noted no 3D metal printing technology would be commercially viable for an MTB crank arm. However, it is conceivable that the price of technology may reduce to enable 3D printed bicycle components soon. The industry has already started to embrace the technology for producing parts such as pedals, accessories and frame connectors. We then analyse the process undertaken and consider how it connects with other aspects of product design practice, particularly its integration with ‘making’ as a core practice.

Results

Topology Optimisation is based on software tools; it was necessary to explore, understand, and select an appropriate software tool for the process. Several tools were considered (see Figure 8). Based on this investigation, Autodesk Fusion 360 was chosen as the most appropriate, reasons for this selection were discussed earlier in the paper. Presented in Figure 9 is the pre-simulation screen inside Autodesk Fusion 360.

[4] It should be noted that this is not an engineering study but rather an investigation of design practice. We consider that the research could be of value to engineering design. Our recommendation is that should the research inspire a design project with an engineering focus; appropriate technical guidelines be taught alongside the topology study to ensure that the optimised solution could be adequately assessed.

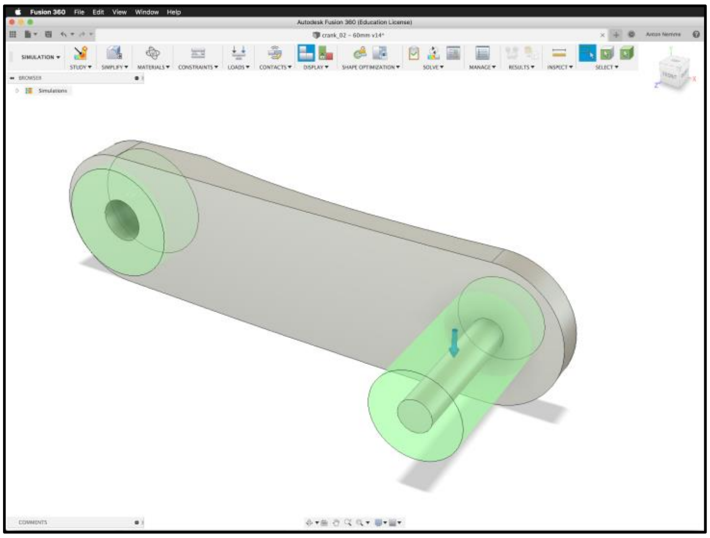

Figure 9. Setting up the parameters for the Topology Optimisation process.

The grey region depicts the shape envelope, the green areas are those to be preserved, and the blue arrow represents the force location and magnitude. The object is also fixed in space via a constraint at the centre of the hole feature. Additional variables such as symmetry and mesh size are also entered. Then a percentage of mass reduction must be chosen for the solver algorithm to begin. This was set at 40%. Then the simulation is run in a cloud-based situation with those variables in place. Figure 10 depicts the result screen from the Topology Optimisation process. Here we can see the shape envelope has been affected, resulting in material removal and an object that appears to have eroded. This result screen allows the percentage of mass reduction to be varied on the fly via a slider that manipulates the boundaries of the eroded mesh structure. Areas under the highest loads are shown in red and under the least in blue, with intermediate colours in between. The green zone is optimum for the amount of material reduction set in the solver. This process was repeated six times; in each situation, adjustments to the variables were made (including mesh density, symmetry and protected regions), and each optimised object was saved as a polygon mesh and printed in ABS using a UP Box FDM desktop 3d printer. The array of optimised models A-F is shown in figures 11 and 12.

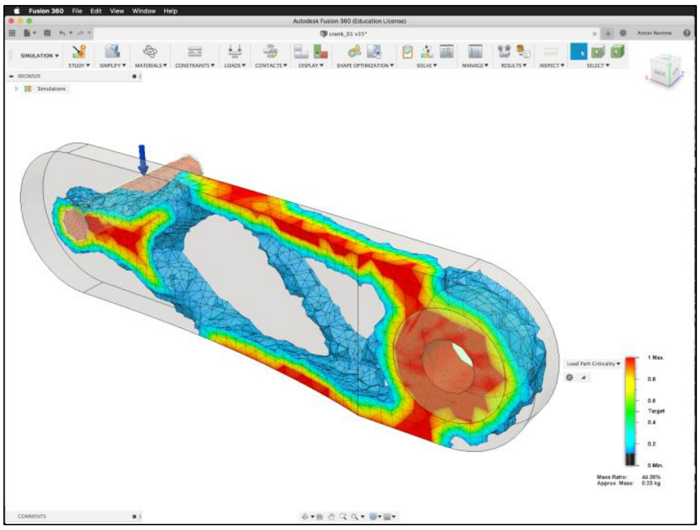

Figure 10. The result of a Topology Optimisation process

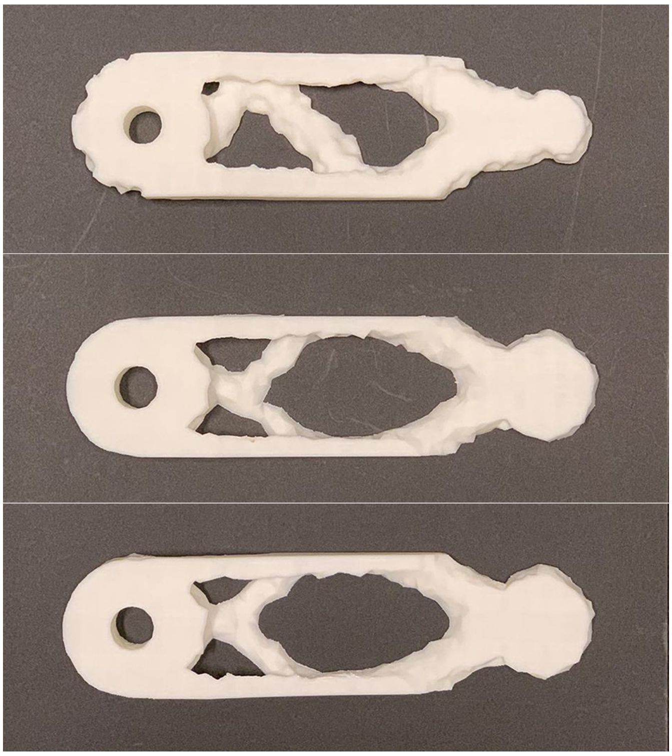

Figure 11. Topology optimised models A-C. Model A (top) - Coarse mesh, no symmetry, small preserved region around pedal axis. Model B (middle) - Medium mesh, no symmetry, large preserved region around pedal axis. Model C (lowest) - Medium mesh, symmetry, large preserved region around pedal axis.

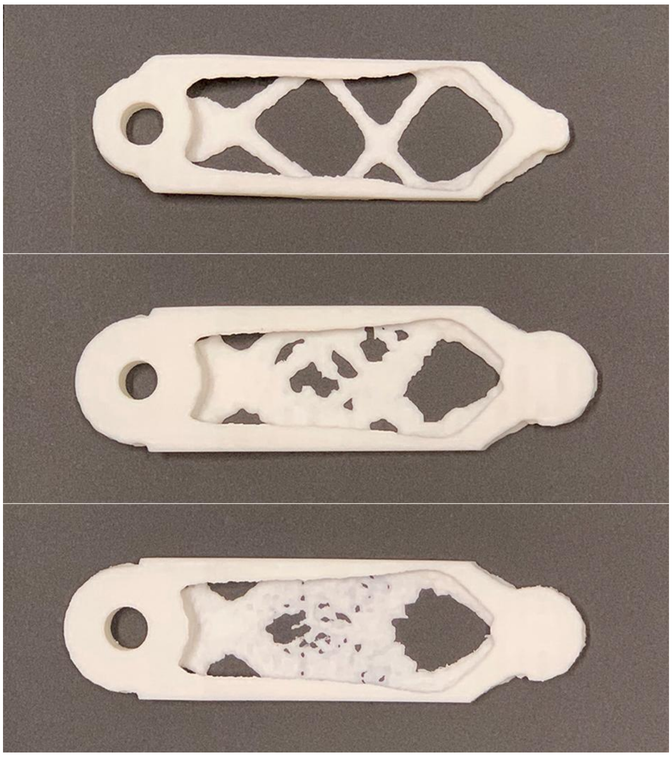

Figure 12. Topology optimised models D-F. Model D (top) - Fine mesh, no symmetry, small preserved region around pedal axis. Model E (middle) - Fine mesh, no symmetry, large preserved region around pedal axis. Model F (lowest) - Fine mesh, symmetry, large preserved region around pedal axis.

Conclusion

This paper investigates computational generative design and topology optimisation as a part of product design practice. It provides considerations for their incorporation into a design curriculum for University product design programs. The authors undertook a review of research literature on generative design, topology optimisation, and the role of iteration and innovation in design practice. To contextualise the information from the literature review, we engaged practice-led research to design an MTB bike crank arm using the technology. Critical steps in the process were recorded so that we may address the following questions:

- How can we synthesise and implement the emergent tools in the landscape of computational design to augment the arsenal of tools and methods product designers currently use?
- How will this affect the education of undergraduates and the practice of graduates?

The first question considers that a range of different digital technologies (software and hardware) can be useful to integrate generative and topology optimisation tools with the product design process. Based on a load-case, topology optimisation software can generate a 'working' form that can be directly produced using additive manufacturing technology (capable of making any three-dimensional shape because the printing methods are not constrained in the same way as conventional production methods). Consequently, there is great interest in the technology from an engineering perspective and the question of where product design 'fits in'. Research indicates that product design employs iteration (as a part of reflective practice) to improve and innovate concepts. Iteration and divergent thinking are essential parts of design practice to be supported in education. Physical modelling (making & testing) and sketching are excellent modes of practice to assist that 'thinking and learning' process.

Our research uses Autodesk Fusion 360 to optimise topology and generate concept variations within design constraints. These concepts have been printed in ABS using an FDM printer to analyse the physical parts. The software can generate new ideas based on iterating through various constraint combinations such as load-cases, mesh densities and boundary envelopes. Concepts can be saved during the process and then printed in groups. Printing is not a strict requirement, but we find it an essential part of the reflective process. A closer examination of the physical form (and combinations of physical variations) can help determine the best avenues for further surfacing refinement and production methods.

It's important to consider that the production method need not be additive manufacture and might be other types of fabrication such as CNC machining. Technology-enabled design iteration and making (via 3D printing) employs the same reflective critical analysis that product design has always valued. Where engineers may focus on part performance as a priority, product designers can use the technology to investigate the intersecting concerns of part performance, styling and varying combinations of materials and production methods.

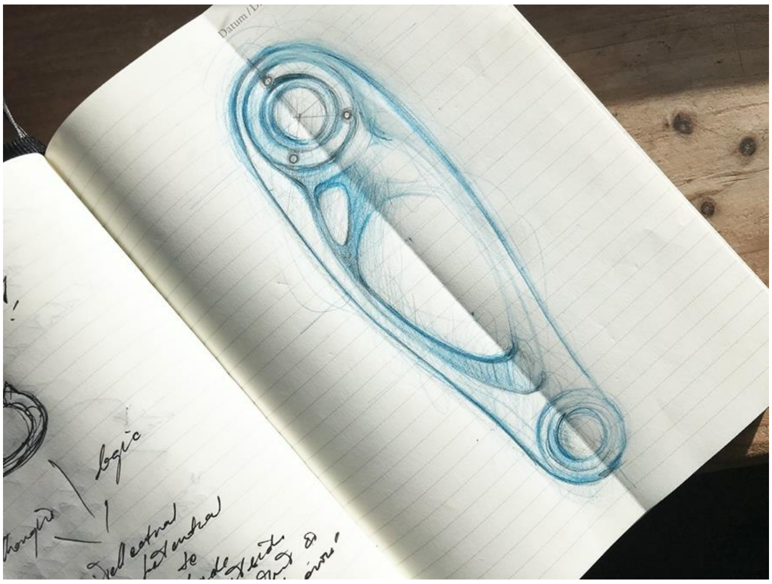

Figure 13. Crank sketch by Roderick Walden, which used the selected topology study as form inspiration. A clear connection with the revised crank design produced by Gianfranco Lassandro (see figure 14) is evident.

In response to the second question, the project has revealed that using topology optimisation as a generative design method may apply in early and later design development stages. However, design fixation and the facilitation of divergent thinking must be carefully considered. In the case of a MTB crank arm, it may be essential to consider the range of bicycle riding approaches, material choices and the aesthetic style that users may be responsive to. The load-case is not the only consideration for the designer. For example, early-phase use of the technology may explore variations in boundary constraints. A more specific set of controls, including a well-researched load case, can be applied to generate more ‘finished’ designs for the refinement phase. However, we find that these more refined outcomes (from the software) are most likely to require further design detailing to translate the ‘lumpy’ forms generated by the software toward more stylistically refined surfaces employing the shape study as a ‘substrate’ for applied surfaces and edges. Ideas for how these might develop, based on our case, are presented in the discussion section.

Discussion

Generative Design and Topology Optimisation tools have matured and reached a level of sophistication where they are helpful and benefit the design process. With application to form generation, these tools and processes may be a way to claim some territory in engineering problems as simulation results can inspire effective structural strategies in an early phase of the design process. It is important to note that these new processes may alienate designers who work traditionally unfamiliar with the processes, terminology and software tools. In the same way that product design programs have embedded Additive Manufacturing principles into design education, it is the role of product design educators to do the same for Generative Design. From this perspective, we can say that It does not supplant traditional design processes but can augment and inspire them.

In terms of preparing our students for a future in the workforce and the world of design, understanding Generative Design and Topology Optimisation methods are fundamental as it permits a change in how a design process might be conducted. Furthermore, as Additive Manufacturing allows the manufacturing of complex forms, Generative Design and Topology optimisation are likely to be more leveraged to progress to a manufactured output.

Refinement of optimised forms

As stated in the conclusion, the topology optimisation process generates forms with ‘lumpy’ surfaces and fills the boundary area (set by the designer) in (let us say) inelegant ways. TO methods may be appropriate for brackets hidden behind housings, but the raw computer-generated optimisation output is unlikely to be attractive to the consumer for a visible product. Product designers must be concerned with more than the engineering performance of a design. Therefore, we recommend that a follow-up process of design refinement be engaged. Although some CAD software tools make it possible to ‘smooth out’ a simulation result, we consider that for this MTB crank arm, a more disruptive interpretation of the results is necessary to resolve the aesthetics to a level of sophistication in-line with market expectations. The renderings below (Figure 14) represent the results of this follow-up process. Details of this stage are beyond the scope of this paper; however, we suggest that more traditional sketching (Figure 13) and modelling practices can come back into play to inform further computer modelling, testing (FEA) and printing of the finished design, ready for production analysis and commercialisation.

Figure 14. Potential concept directions that explore surface refinement of the optimised computer models. The models presented above were created by Gianfranco Lassandro using Solidworks and KeyShot based on a selected topology optimisation study issued to him as a CAD file. Gianfranco Lassandro is a sessional lecturer at UTS and a professional industrial designer based in Sydney, with clients in Australia, Europe and the U.S.A.

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