Generative Design

Recommended actions to smooth the way for production of generative designs with additive manufacturing

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Abstract

Generative design is a new method which allows designers and engineers to insert certain constraints and parameters in a CAD(Computer-Aided Design) programme. This information is used by the software to generate a variety of CAD models adhering to all constraints and formed in various compositions without intervention by the designer. Using this process can result in quicker, more structurally sound and less conventional designs compared to the traditional design process. This study assessed how generative design can be used in combination with FDM(Fused Deposition Modeling) for SME's(small and medium-sized enterprises). A combination of literature research, market research and research into current CAD software was used to answer this question.

Results indicated that the current state of generative design is not viable for SME's to use and include in their current design process. The research question was changed to answer the question which actions are required from involved parties to make generative design a viable option for SME's in combination with FDM. The result was a roadmap that shows all actions that need to be taken before generative design can be incorporated. The conclusion is that generative design is not yet viable in its current state and time is necessary to complete the actions in the roadmap. Future research is necessary to see if these actions aid in the progress of incorporating generative design in the design process of SME's.

Preface

Dear reader,

In front of you is my thesis regarding generative design, an exploration of its current state of the art. I used several research methods to discover why generative design is currently still a fun novelty to play with , instead of an integrated design tool in CAD software. The results of this thesis highlight changes which are necessary to implement generative design in the current market.

This thesis was conducted according to the graduation requirements for the master Industrial Design Engineering at the University of Twente. The company CAD2M provided an graduate internship and requested research into generative design to acquire information. They provided me with the necessary tools and software required to conduct my research.

I was working on my thesis during the COVID-19 pandemic, from March 2020 until March 2021. It was a very strange experience and the social isolation was a difficult time for me personally regarding motivation. Nonetheless, I am still very proud of the results I acquired during this period.

I would like to thank Michel Klein-Wassink from CAD2M for his support and assisting me with his personal experience in the CAD world. Ilanit Lutters-Weustink from the University of Twente for the multitude of video meetings and assistance regarding the research aspect of the thesis. Janwillem te Voortwis who was 'locked up' with me together. Last but not least, I would like to thank the employees of CAD2M, family and friends who provided me with support.

I hope you enjoy reading my thesis.

Kind regards,

Claudia Westerveld

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Nomenclature

Computer-Aided Design	CAD	Designing products with the help of computers.
Computer-Aided Manufacturing	CAM	CAM software loads computer-aided design models and can produce the correct machine code, also known as G-code, so machine tools can fabricate the model.
Computer-Aided Engineering	CAE	Software that assists engineers during the analysis process. A few examples the software can perform are FEM simulations, fluid dynamics or topology optimisation.
Standard Tessellation Language	STL	A file format in CAD software used for additive manufacturing. STL files contain information about the 3D model by using many small triangles which cover the surface of the object.
Support material		Different material in comparison to the material used in the 3D printing process. This material supports overhangs or other weak points of the part during printing. Afterwards, the material can be removed because it can dissolve in water. It can also be the same material and then it will print in a lattice structure which can be easily removed physically.
Additive manufacturing	AM	A manufacturing method that takes data from a CAD model and builds the physical representation by adding layer-upon-layer of material.
Design space		All values and combinations of controllable parameters that yield attributes within the specifications by the user.
Parametric design		A process that uses expressions of rules and parameters. These parameters are defined by a user which allows algorithms to use the available data to build a design.
Geometric model		A geometric model, also known as a CAD model, is a digital representation of a physical design and made using CAD software. It describes geometrical relationships of the design and holds information about properties such as material or weight. CAD software uses geometric models to evaluate designs for physical characteristics such as Von-mises stress or aerodynamics[2].
Plug and play		Software and hardware which works perfectly when first used without any interference or adjustments from users.
Ductility		The measure in which a material allows for plastic deformation. A low ductility means a material will break soon when elongated, otherwise known as a brittle material.
G-code		A numerical control programming language which is used to control automated machines. The G-code tells the machine what it needs to do, in which order, with which tool, in which place, etc..
Design intent		The design intent is how your model behaves if dimension or parameters are modified. If one part changes, that change is automatically transferred to other parts.
Isotropy		A material is isotropic if its properties do not depend on the direction. If the properties do depend on direction, the material is anisotropic.

Fused Deposition Modeling	FDM	A subprocess of additive manufacturing in which viscous material is extruded through a nozzle onto a build plate.
Small and medium-sized enterprises	SME	SME's are companies with less than 50 employees(small) and between 50 and 250 employees(medium).
Traditional subtractive manufacturing		Manufacturing methods which have been used for a very long time. Examples are methods such as drilling, turning or casting. In contrast, additive manufacturing is a new method.
Product development process		This is a process which contains all the steps necessary to take a product from its concept to the market.
Design process		A process within the product development process which only involves the design of the product from concept to its evaluation.
Architecture, Engineering and Construction Industry	AEC	An industry sector enveloping all involved industries which are necessary to bring construction projects to its fruition from design to on site construction.
Finite Element Method	FEM	The FEM is a numerical method that can solve mathematical equations such as differential equations. It is used in engineering industries to help with fluid dynamics or structural analysis.

PART

Preliminary research

Chapter 1
Introduction

The subject of this thesis is introduced in addition to the problem statement. Simplified background information is given in order to explain the importance of the subject. The introduction ends with the research question.

Chapter 2
CAD2M

The assignment provider, CAD2M B.V., is introduced. Their vision about the importance of generative design is explained and why it is important for them and their clients.

Chapter 3
Generative design

Misconceptions about the definition of generative design and its meaning exist across several sources. This chapter defines a fixed definition and resolves any misunderstandings about the concept.

Chapter 4
Additive manufacturing

The combination of generative design and additive manufacturing makes a powerful tool. This chapter explains why that is the case and how to engineer good designs for the fused deposition modelling process.

Chapter 1

Introduction

In this chapter, I will introduce the concept of generative design and its advantages. This method, together with the introduction of additive manufacturing, will make for a powerful tool which can benefit smaller companies. I present the problem statement, related research question and expected results and will end the chapter with an explanation of the layout of this thesis.

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1.1. Introduction

Decades have gone by where the product development process has been constant and rigid[2]. Designers and engineers develop beautiful concepts only to be limited by performance requirements and manufacturing limitations. A multitude of design iterations later, the final product might not match with the designers' first intention. Redesigning and tweaking concepts into a design, which meets the functional requirements as well, results in an unnecessary waste of time and money.

Recent years have shown tremendous progress in the intelligent design automation technology[2] which can alter the future of Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE). Improved computing power and working in the cloud allows companies easy access to a fairly new process called generative design. This method can accelerate and optimise the product design process using machine learning and pre-defined algorithms.

Generative design allows software to generate a multitude of different designs using a viable design space and criteria[3, 4] defined by the user. Designers can specify geometry, forces and fixtures as well as maximum costs, manufacturing process and various other parameters. The system calculates and presents various designs that meet the user's requirements by applying certain algorithms[5] as seen in Figure 1.

Generative design grants designers and engineers the ability to be more exploratory with their designs[5, 6] because the algorithms do not take into account more traditional compositions[7]. In a short period, multiple designs are generated which are as strong as required, use less material and consume less time of the designers[8].

1.2. Additive manufacturing

As illustrated in Figure 1, most generated designs are very organic in shape with different shaped holes, slopes and forms. Producing these products using traditional subtractive manufacturing methods is a very time-consuming and expensive process[9, 10]. The introduction of Additive Manufacturing (AM) can resolve this problem.

Additive manufacturing is a technology that allows machines to add layers on layers of a wide variety of materials to produce complex shapes[11] using physical or chemical phenomena. A range of seven printing process groups exists in additive manufacturing where one of the more accessible printing methods is Fused Deposition Modelling (FDM), see Figure 2.

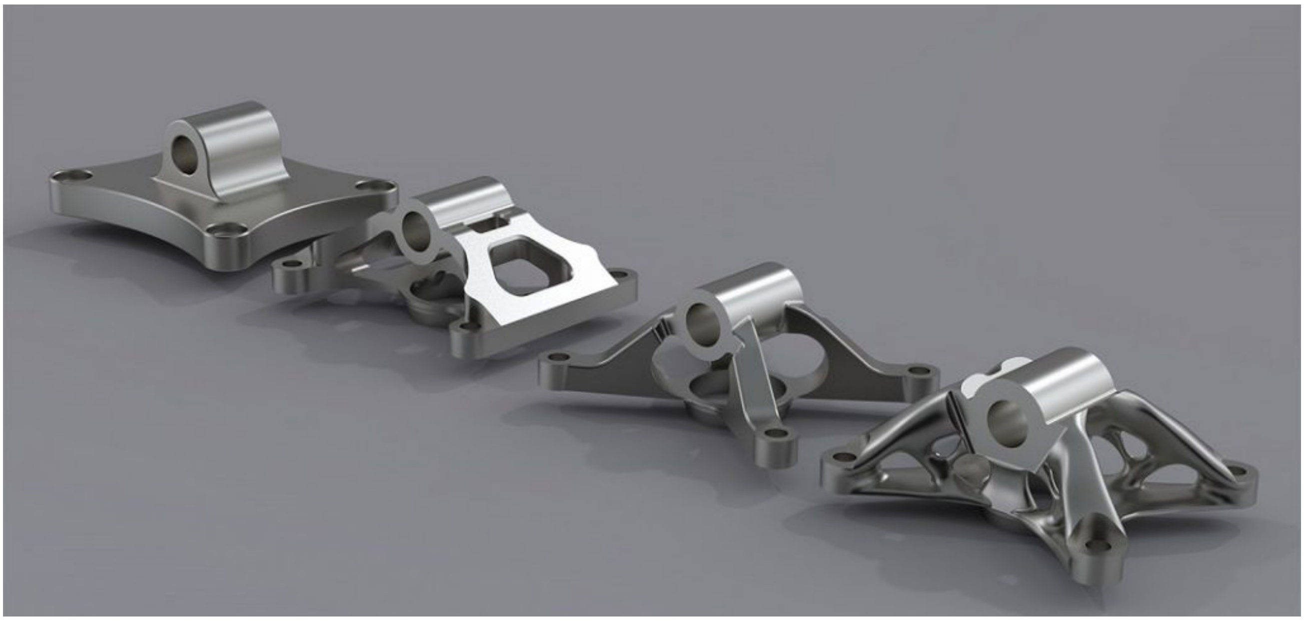

Figure 1: Three generated designs resulting from the initial requirements shown in the upper-left corner[9]

FDM deposits a viscous heated material onto a build plate layer by layer. When it cools down it adheres together and forms a product. Due to the layer-by-layer production method, very complex shapes can be produced[11]. FDM is cheaper compared to other additive manufacturing methods, has a wide variety of available materials and has a short lead-time[9, 12].

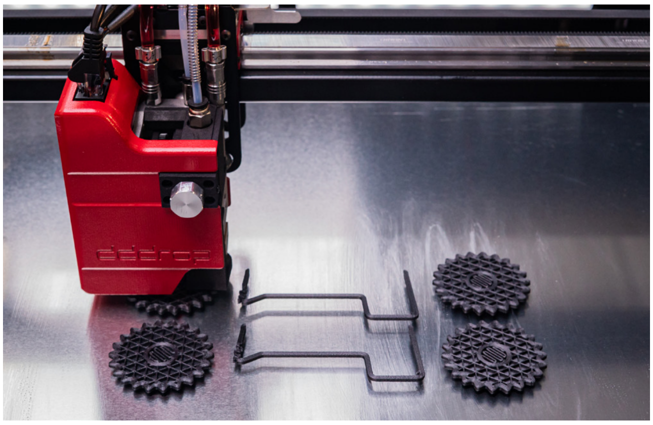

Figure 2: FDM printer

1.3. Problem definition

A large amount of Small and Medium-Sized Enterprises (SME) in the manufacturing industry is now entering the 3D printing market and discovering its possibilities for improvements in the design process. Respectively, SME's are companies with less than 50 employees (small) and between 50 and 250 employees (medium). Factors such as object quality, speed, available materials and its prices were influencing SME's to abstain from investing in 3D printers until it was more developed[10]. But cheaper prices and easy-to-use FDM printers have changed their minds.

Generative design in combination with AM is a very powerful tool. The ability to generate thousands of designs adherent to restrictions early on in the design process is a time-saver. Furthermore, computers are not biased towards one concept and the untraditional results are easier and cheaper to manufacture with AM.

The company CAD2M sells FDM printers and CAD software packages to SME's in addition to being a knowledge centre in the engineering and manufacturing market. CAD2M noticed that more of their clients, mostly consisting of SME's, are interested in FDM printers. It is their belief that generative design in combination with AM is the future. To stay ahead of the competition and their customers, CAD2M requires more research in generative design in order to make it easily available to their clients.

Currently, generative design is difficult to use for SME's. It is a fairly new topic which needs to be introduced to SME's and professional CAD software still has limitations. Either the method is not yet implemented in the software they are using or software does not account for the fact that generated designs can be produced using FDM. For example, computational tools such as Solidworks 2020, as will be demonstrated in Chapter 8, generate designs assuming the material is uniform. In reality, parts produced by FDM are anisotropic due to the layer by layer method. This results in designs which are not as strong as predicted or will break when being used[9].

Experimental programmes such as the Dream Lens system, researched and developed by Matejka et al.[13], exist that try to make the approach to generative design easier. However, these products are either not ready for usage in the industry because it is not available publicly or did not account for the fact that designs can be 3D printed.

In conclusion, a change is needed that allows SME's to get an early start with generative design and explore its possibilities. A guiding theoretical framework for generative design is widely recognised as a necessity[3] because there is no software yet that designers want to use[7]. The perks of design exploration, optimised parts and shorter design phases could benefit SME's tremendously. In combination with FDM printers, their generated designs can already be realised and be put into production.

1.4. Research question

For this thesis, research will be conducted to discover how to bridge the gap between generative design and SME's. The goal of this thesis is to make it simple for SME's to start experimenting with generative design in combination with FDM printers. The following research question will be answered, see below:

In addition to the main research question, several subquestions are used to assist in answering the main research question.

- What is generative design?
- How does generative design differ from topology optimisation and biomimicry?
- How does FDM work and which factors have the most influence on the final product?
- What are SME's future goals considering additive manufacturing?
- What are the current capabilities of commercial generative design software?
- What is the current state of the art of generative design?

"How to bridge the gap between SME's and generative design with a set of design rules in order to produce reliable generated designs with FDM printers?"

1.5. Results

After answering the research question, SME's can more easily utilise generative design in combination with FDM. Design rules will allow SME's to use generative design by giving guidance and requirements to minimise mistakes and lessen frustration.

Furthermore, this thesis will help SME's to identify generated designs which will cause problems during the printing process and usage of the products. SME's can check their generated designs and identify flaws before printing the product. Products that are not as safe or strong as required will be eliminated before being 3D printed. This prevents loss of time and material and reduces post-processing steps which are often needed after FDM printing.

Lastly, a recommendation will be written about the future of generative design. Currently, it has many flaws and further research is needed to optimise the process. The recommendation will explain the current situation and highlight essential future work and shortcomings of the method.

1.6. Layout

The layout of this thesis is divided into three parts namely preliminary research, research methods and results. Each part contains various chapters as shown in Figure 3.

In part I, the introduction to the subject of this thesis and the problem statement was given. The second chapter will give more information about CAD2M who is the assignment provider. The structure of the company and the vision they have for the future is given in addition to an introduction of their sister company Dddrop 3D printers. The third and fourth chapter gives the necessary background information needed to understand generative design and FDM.

Part II will start with detailed information about the methodologies used. Specifically, subjects such as the scope, research design, data collection and validity will be explained. The following chapters are the used research methods such as extensive literature research, market research and research into currently available CAD software.

The chapters of part III will begin with a revision of the currently stated research question in the introduction. A roadmap will be used to visually represent the results of this thesis which will be discussed. Lastly, the final chapters are the final conclusion and recommendations for future work.

PART I
Preliminary research

PART II
Research methods

PART III
Results

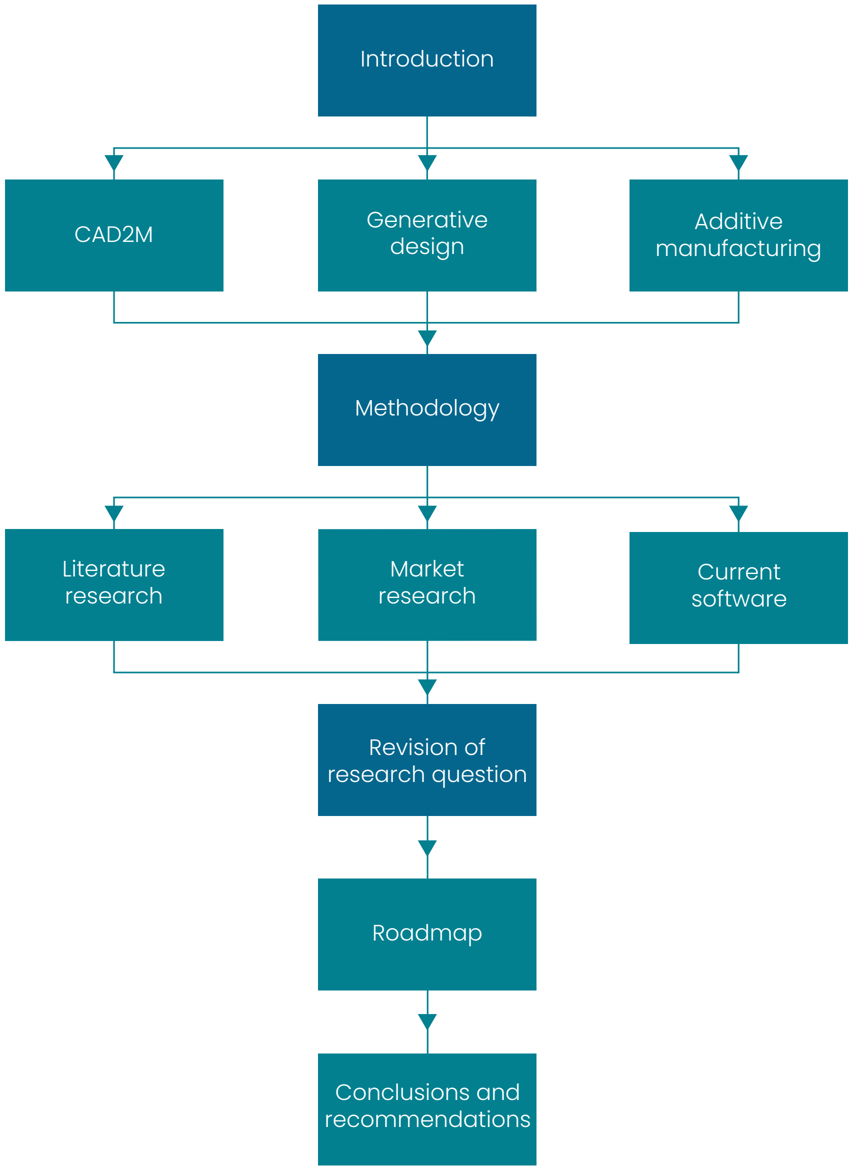

Figure 3: Structure of this thesis

Chapter 2

CAD2M

The previous chapter introduced the assignment provider of this thesis. In this chapter, I will provide a short introduction to CAD2M with an overview of its history, inner workings and the relationship with subsidiary Dddrop 3D printers. The goal of this chapter is to explain why CAD2M wants to invest in generative design by explaining their vision and prospects.

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2.1. CAD2M

CAD2M B.V. is a company situated in the Netherlands, Doetinchem and is an officially licensed reseller of CAD packages developed by Dassault Systèmes. One of the more well-known CAD programmes produced by Dassault is Solidworks. It started as a one-man business in 1991, at the time called Care Innovation, selling 2D CAD systems.

Eventually, the company expanded and started selling 3D CAD programmes in 1995. This market grew exponentially when Solidworks became available for Windows systems and CAD2M began to expand. In 2000, Care Innovation added Computer-Aided Manufacturing (CAM) to their specialisation and in 2003 the name officially changed to CAD2M. In 2007, CAD2M began selling FDM printers developed by Stratasys until eventually, CAD2M released their own FDM printer in 2013 under the name of Dddrop.

CAD2M is currently working on helping companies get familiar with the new cloud platform of Dassault Systèmes, namely 3Dexperience. A timeline of the company CAD2M is shown in Figure 4.

2.1.1. Unique value proposition

CAD2M is a unique company compared to its competitors. While they resell software packages from Dassault Systèmes like their competitors, it also offers continuous support and aid. They give training courses in various aspects of the Solidworks package, have a technical helpdesk and offer consultancy. Their unique value proposition is continuous aid, top-notch customer support and a source of domain-specific knowledge and ideas. Their core activities are illustrated in Figure 5 which shows their main focus as CAD, CAM, Product Data Management (PDM) and 3D printers in addition to their activities that orchestrate it.

2.1.2. Clients

Currently, CAD2M has around 2400 clients, varying from SME's to self-employed professionals, who can approach them for help with their CAD and CAM in Solidworks. Figure 6 shows an estimation of the ratio of their clients. Their more well-known clients are MechDes engineering, an engineering bureau, AWL who develop welding robots and the Accell Group who produce bicycles for Batavus.

2.2. Dddrop 3D printers

Dddrop 3D printers is a sister company of CAD2M and produces FDM printers. In the past, CAD2M sold Stratasys 3D printers. When they stopped selling them, CAD2M discovered that companies were still looking for more reliable FDM printers which were suitable for industrial purposes. For the additive manufacturing market, FDM has the biggest market segment for SME's since it is one of the cheapest 3D print techniques, easy to learn and needs less post-processing according to Dddrop. Which is why engineers in CAD2M used the knowledge they had gained from selling Stratasys to build their own FDM printer. Their first printer was the Dddrop

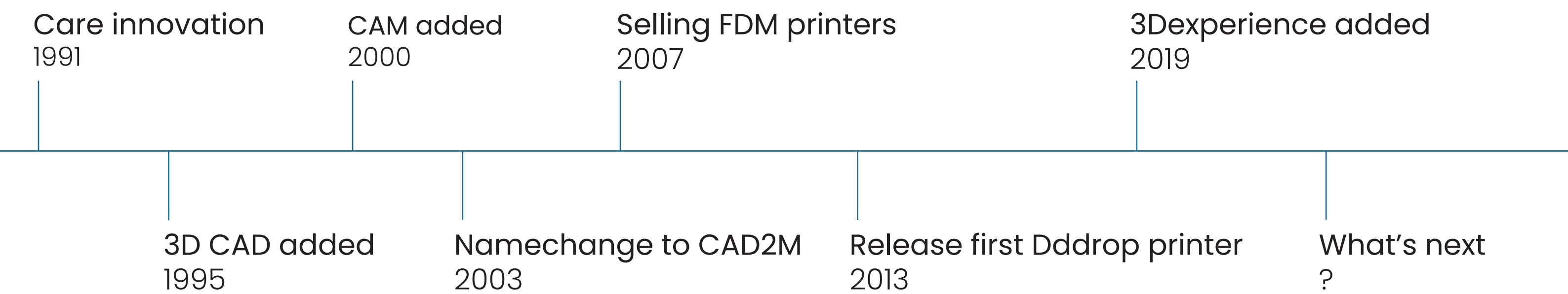

Figure 4: Timeline of CAD2M

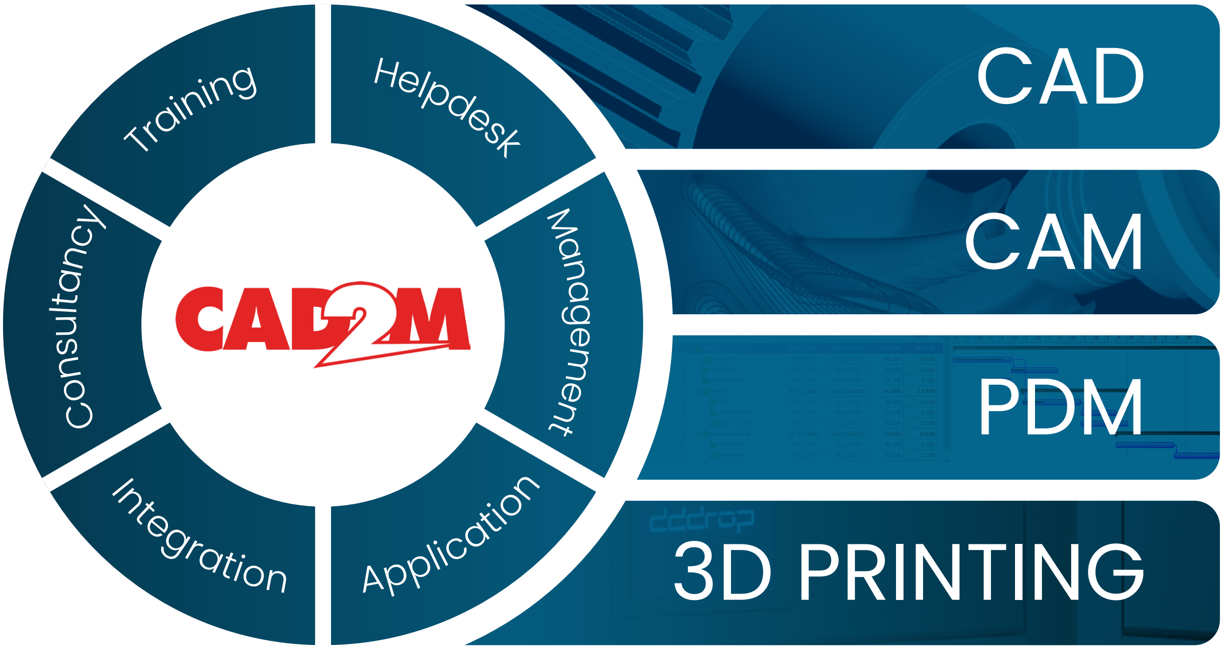

Figure 5: The activities of CAD2M

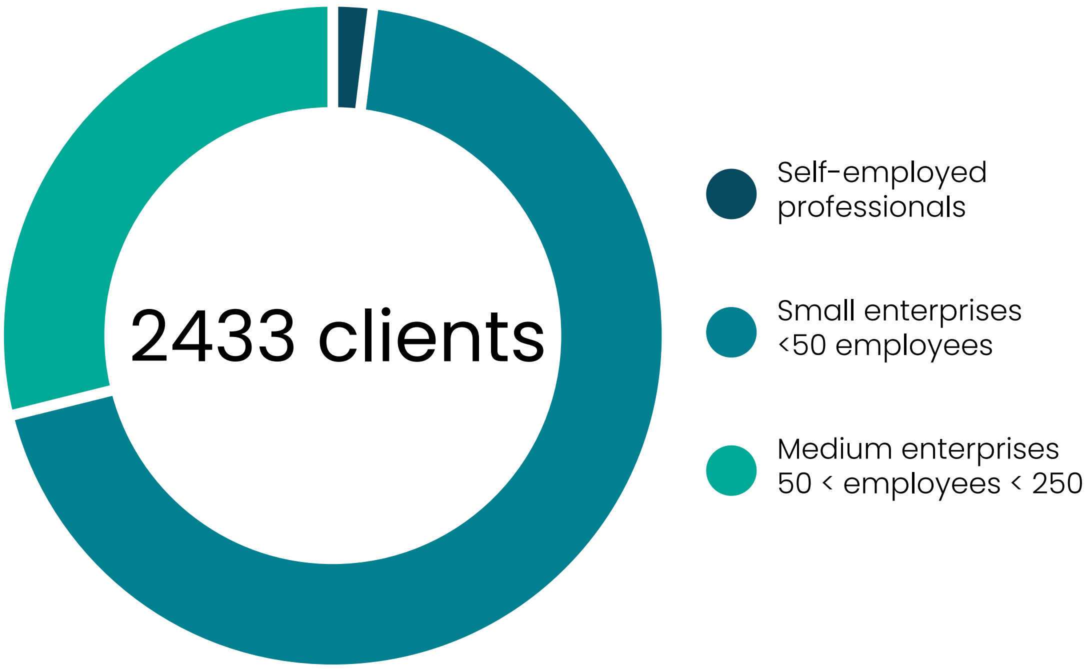

Figure 6: The ratio of clients of CAD2M in 2020

Recon which had the goal to discover what the market was looking for. After its success, a product line of various printers followed with the Dddrop Rapid One being the latest addition as seen in Figure 7.

Dddrop offers industrial FDM printers which are easy to use, reliable and will make 3D printing less of a hassle. CAD2M's target group are SME's in engineering industries who are curious but still hesitant about the advantages of 3D printing. That is why the printers of Dddrop do not have any new gadgets or techniques, but rather consist of a reliable set of features in their printers which makes them more stable and consistent. The printers have a smart module which allows users to control their printer from the web or their mobile phone. Furthermore, this module will tell users if there is something wrong with the print or the procedure so users can act accordingly. This smart module offers clients to walk away from a print during the process without worrying and reduces errors.

2.3. Prospects of CAD2M

To stay ahead of its competitors and customers, CAD2M wants to invest in knowledge of generative design. They believe that generative design is the only step forward. Due to progression in additive manufacturing technologies, generative design can now be realised physically. As of right now, their clients are only just discovering the possibilities of FDM printers and have not yet explored generative design.

CAD2M has already ventured into research on generative design. They cooperated with a student from an university of applied sciences. His focus was on what exactly generative design entails and the opportunities it can bring[15]. Unfortunately, the topic was too broad to give definitive conclusions and CAD2M knew more in-depth knowledge was needed in certain areas.

Thus, CAD2M provided the challenge to gather more specific knowledge about generative design in CAD in combination with the packages of Dassault Systèmes and their Dddrop printer. Their interest is mainly in gaining as much knowledge on this topic as possible because they believe that generative design will become more relevant in the future. In other words, they want to be prepared when generative design will ultimately become part of the market so they can provide this knowledge to their clients.

The potential added value for CAD2M is extensive because it gives them a knowledge advantage in their current market. If companies have questions about the generative design process, CAD2M will be able to offer answers. Greater knowledge in generative design can also help to assist their clients in optimising their CAD designs.

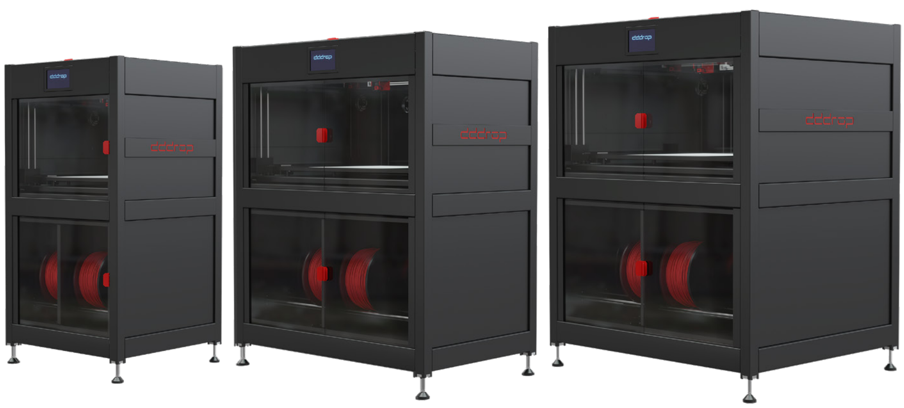

Figure 7: The Rapid One modular printer by Dddrop 3D printers

"CAD2M believes that better products will result in a better world. They want to stimulate innovation by providing tools to help people realise their amazing ideas into real products. As a dependable partner, they pave the way for product realisation by sharing their knowledge, support, software and hardware[14]."

Chapter 3

Generative design

In this chapter, I will provide the necessary background information about generative design. Before answering my research question, it is important to avoid any misconceptions about the method and understand what the difference is between generative design, topology optimisation and biomimicry. I will focus on developing a fixed definition of generative design and explaining the advantages and disadvantages of generative design.

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3.1. What is generative design?

At the time of writing, generative design did not have a fixed definition. That is to say, the term has not yet been introduced in the dictionary and most people have their assumptions about generative design. Among researchers, there is discord about its exact definition although their definitions all point in the same direction. A few of them are given below:

In conclusion, researchers seem to agree that generative design is a method which lets computational models use input from users to generate new designs. During the generative design process, there is little to no human intervention. To avoid confusion, this thesis gives one clear definition of generative design which is illustrated in Figure 8.

Dhokia et al.[6] describe generative design tools as media to create concepts from requirements, constraints and goals.

La Rocca[16] thinks generative design is a methodology in which input is given by a user such as dimensions, durability or other restrictions which the system should account for. A generative model, which uses a set of rules, is used to determine how the design can look.

Rodrigues et al.[17] talk about generative design methods that utilise algorithms to produce a large number of new and alternative design solutions in an automated procedure.

Oh et al. [18] state that "generative design aspires to explore the design options that satisfy structural performance and choose suitable designs for various designers' needs".

Definition of generative design

Generative design is a method which allows users to give various inputs and restrictions to a system without providing a complete geometric model. The method has a generative model, with algorithms that adhere to certain rules, to optimise the designs according to the wishes of the user. This generative model will create its own geometry and reiterate designs while adhering to the given instructions until no more suitable designs can be found. The process gives multiple outputs to the user in the form of tangible designs such as 3D models, drawings and/or simulations of the desired product.

3.2. Current status

Generative design sounds promising but it is still in its early development. A few early adopters such as Black and Decker and Airbus seem positive about its prospects. Bastian Schäfer, innovation manager at Airbus, when talking about generative design boldly states that: *"This is the direction in which we are headed.[2]"*

While generative design could offer solutions for complex problems, at the time of writing there are still complexities which prevent optimal usage. In the following paragraphs, a summation is given about the pros and cons of generative design.

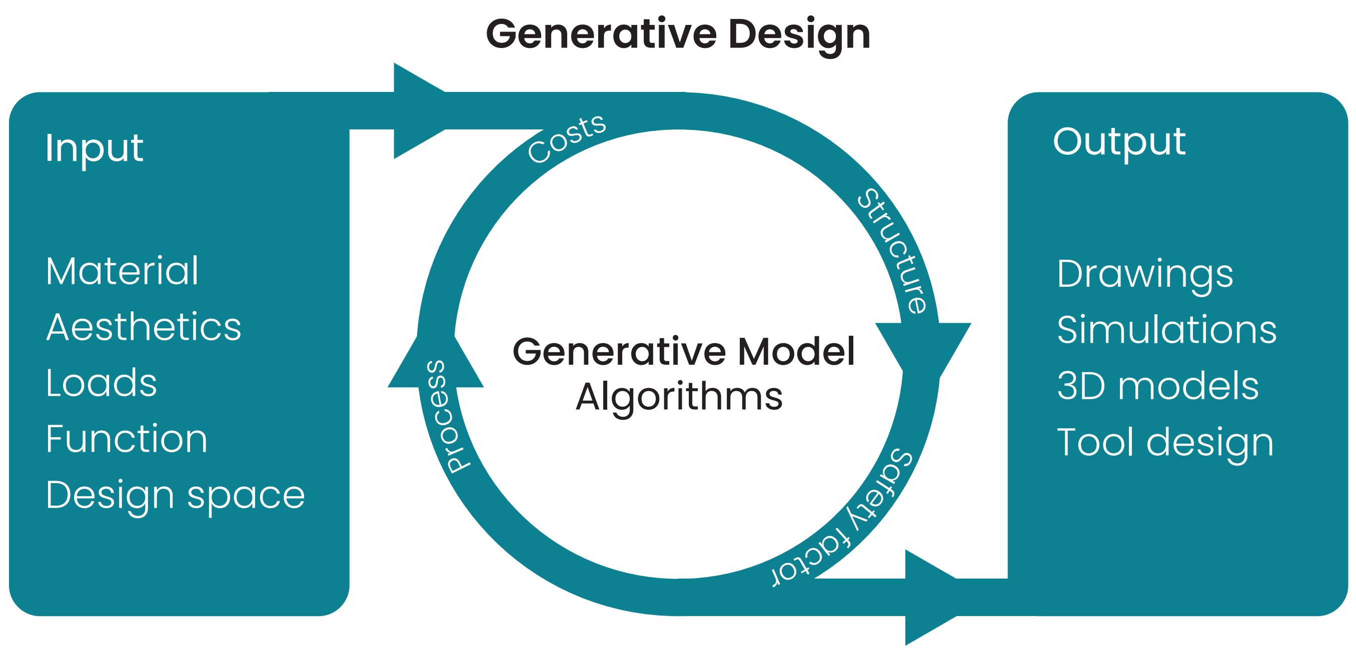

Figure 8: The generative design process

3.2.1. Advantages

Generative design has a more streamlined product development process in comparison with a traditional component design process, see Figures 9-11. In the generative design process, CAE is done before the CAD process. It eliminates the check on performance requirements after each design so design iterations become unnecessary.

Furthermore, generative design can provide multiple design solutions during the CAE phase that meet all performance requirements simultaneously[2]. All the designs are generated very rapidly and this not only frees up time for designers to focus on other aspects but also benefits the eventual quality of the product.

The problem is that humans have yet to move away from more traditional compositions based on repetition and symmetry[7] while generative design can help to explore new designs[3, 6, 20]. In comparison to humans, the system is not 'biased' when designing[2]. This results in designs which human designers would never consider.

In addition to more creative solutions, generative design often utilises topology optimisation algorithms which determine the distribution of material within the design space to achieve the best performance according to the restrictions given[20]. This results in designs which do not contain any unnecessary material in comparison to designs made by humans. Furthermore, all the designs which are generated comply with the wishes of the client.

Lastly, generative design offers some advantages which are not directly related to the product development process. It can improve and enhance communication within the company between different functions[2]. For example, designers and engineers can involve branches such as sales, marketing and manufacturing earlier on in the process to make decisions about manufacturability, price and costs. This can prevent miscommunication and helps colleagues to be on the same page.

3.2.2. Disadvantages

Unfortunately, generative design also comes with a set of disadvantages. First of all, when the system has generated a 'viable' design, it is necessary to do an extensive simulation. The system does not know how the product will be used and only considers the loads and properties given by the user. It is still very difficult to insert correct parameters, see Chapter 6, and a validation simulation is needed to confirm the design meets the criteria[8].

Secondly, fear exists that designers will eventually be replaced by computers[2]. But in reality, generative design is an additional tool in the designer's and engineer's toolbox[8]. A human still needs to validate the design, make the final decisions and make adjustments to a generated model if necessary[21]. Additionally, certain requirements such as aesthetics are very difficult to include in a computer algorithm[2], so human involvement is still required.

In addition to fear of the software becoming more important, designers are also hesitant to adopt an entirely new approach[2, 19]. Questions arise such as: *"Who is going to use generative design?" "When to apply it?" "When can you trust a generated design?"* It is difficult for engineers and designers to completely change their design process. A transition period is necessary before implementation is possible.

The manufacturing method is also a concern. The traditional production methods are often unable to produce the intricate shapes of generated designs. Companies and their engineers will need to adjust their production methods which can become expensive and time-consuming.

Lastly, an advantage of generative design is a disadvantage at the same time. Multiple designs make it difficult for designers to analyse and compare designs simultaneously[13]. This is not a problem when the method only offers four solutions, but if the software gives thousands of solutions it does become a problem. The software needs to include extensive filters, refined user interfaces and visualisations to master the design selection[2].

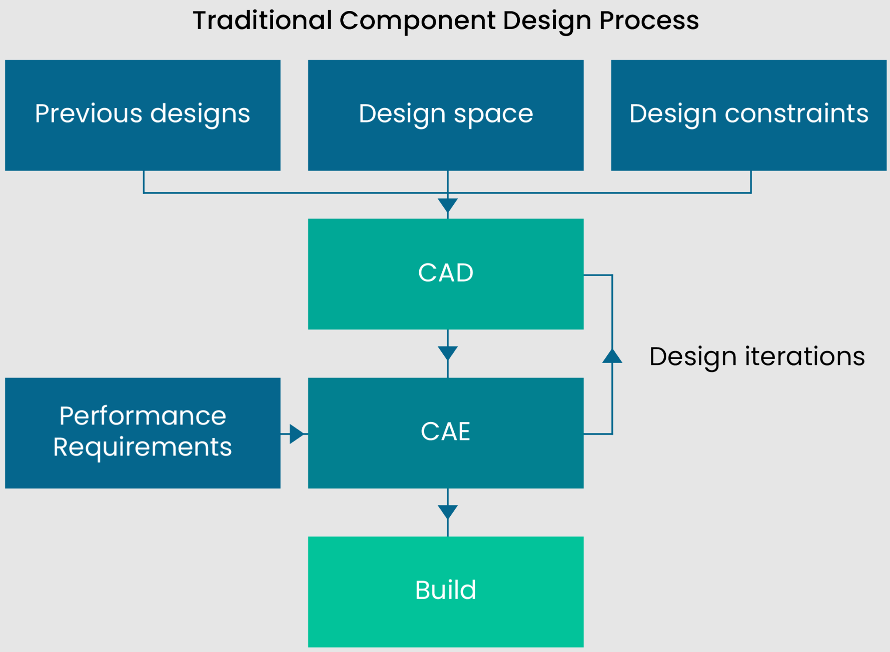

Figure 9: Traditional design process[19]

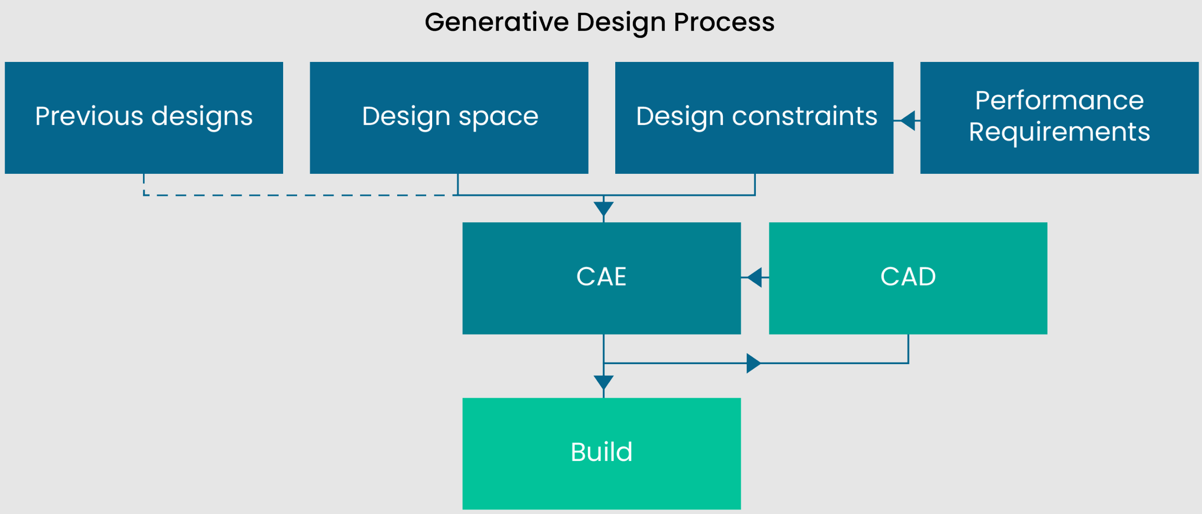

Figure 10: Generative design process

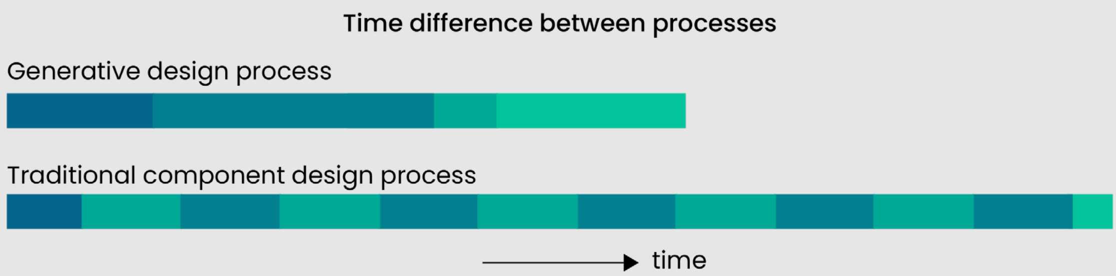

Figure 11: Relative difference in time between the two processes

3.2.3. Conclusion

In summary, the advantage of generative design is the offer of creative, faster and optimised design solutions. On the other hand, the difficulty to use and misconceptions about generative design is holding progress back. Despite the possibility nowadays to use AM and produce intricate products, generative design is still in need of improvement. A summation of the general pros and cons is given in Table 1.

Nevertheless, generative design opens up many doors for designers to break through the traditional methods of designing and exploring new possibilities. It can optimise designs in ways humans never could while keeping costs or material usage to an absolute minimum.

But first and foremost, companies should try generative design before making assumptions about its capabilities. James White, director of the AM strategy practice at CIMdata sums it up in the following quote on the right page:

Advantages	Disadvantages
Design exploration	Generated designs still need extensive simulations
A streamlined product development process which is faster	Difficult to insert correct parameters to achieve all criteria
Multiple design solutions	Fear that generative design will replace the designer
Fast design generation	Difficult to adopt an entirely new process
No designer's bias	Multiple designs make it difficult to analyse and compare them
Initial designs adhere to all requirements defined by the user	Adjustments in generated designs are still necessary
Better product performance	Learning and investing in new manufacturing methods

Table 1: General advantages and disadvantages of generative design

“ The biggest challenges have to do not with the technology itself, but with the ability of humans and human organizations to truly adopt an entirely different approach.[2]”

3.3. Topology optimisation

The term 'topology optimisation' is often confused with generative design but there is a distinct difference. According to Lohan et al.[20] topology optimisation entails algorithms that determine the distribution of materials within a certain domain to achieve the best structural performance with the least amount of material. A topology optimisation algorithm is unique compared to most algorithms because it can create, merge and split interior solids and holes during the recursive iterations[22].

Moreover, topology optimisation algorithms always seek to find the most optimal design[18]. In other words, a pure topology optimisation algorithm produces a single solution while generative design presents a multitude of different solutions. Topology optimisation is very much focused on the best engineering performance[18]. Other algorithms in generative design might have other purposes, such as design exploration or cost reduction, and might forego optimal performance. The distinction between a human designer, topology optimisation algorithm and generative design is illustrated in Figure 12.

It is also difficult for new users to know when to use topology optimisation or generative design. Table 2 shows a variety of use cases and indicates which method is the best candidate for the job. A good rule of thumb to remember is that if you already have a design but you want to structuralllly optimise it, choose topology optimisation. Does a user need multiple suggestions or solutions without providing a fully defined CAD model? Then generative design is the best option.

A reason why generative design and topology optimisation are often confused with each other could be because topology optimisation is an algorithm which is used in generative design[20]. Therefore, generative design is often associated with products that contain organic shapes, which is a trademark sign of topology optimisation.

In conclusion, the distinction is that generative design is the whole process from an input, generative model to output. Topology optimisation is an algorithm that can be part of the generative model as seen in Figure 8.

Use case	Topology optimisation	Generative design
A current design needs to be optimised structurally.	✓	
A user wants shape suggestions for a new design.		✓
A generated design has a nice aesthetic but a user wants to improve its structure.	✓	
A current design is good but a designer would like to improve its design on constraints such as aesthetics.		✓
A new design is made but needs to be structurally optimised	✓	

Table 2: Different use cases for topology optimisation or generative design

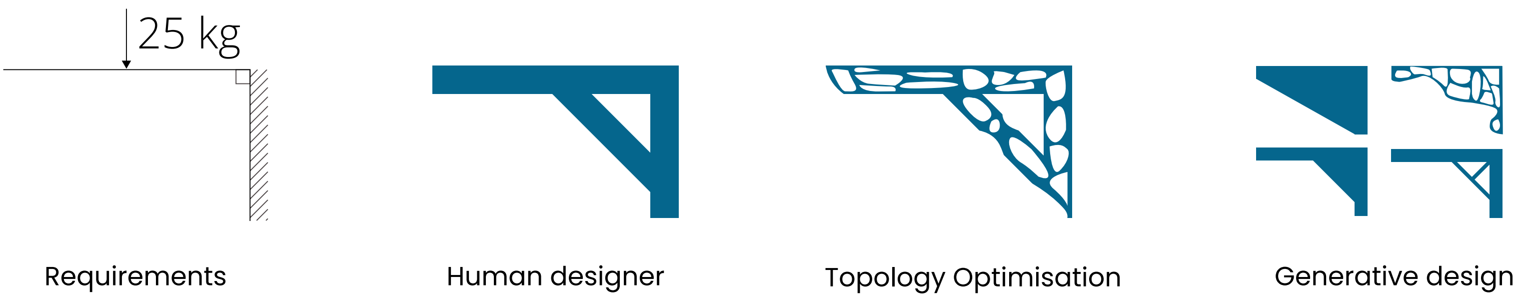

Figure 12: Differences between the 'designers' using the same requirements

3.4. Biomimicry

Another term that is often used in generative design is biomimicry which involves the understanding of biological organisms, structures and functions[23]. It entails studying biological systems to either solve engineering problems or apply knowledge learned in engineering applications[24]. For example, Velcro was inspired by the Burdock plant which uses very tiny hooks at the end of its leaves to attach itself to the fur of animals[25]. Figure 13 illustrates how one side of Velcro consists of hooks, similar to the Burdock plant, while the other side has loops in which the hooks can attach like fur.

Because generative design methods often create designs with complex and organic shapes, they are often referred to as biomimetic[24]. According to du Plessis et al.[24] generative design is, in reality, biomimetic because it is iterative and therefore is similar to evolution as seen in nature, albeit in a shorter period. Similar to AM which Du Plessis et al. see as biomimetic if organic-looking structures such as latticing appear. Latticing appears in almost every AM product due to latticework in support material.

Meintjes disagrees with Du Plessis et al. and thinks that generative design is not necessarily based on organic processes[27]. The author of this thesis agrees that generative designs are only biomimetic if the algorithm used in the generative model is inspired by nature. For example, Dhokia et al.[6] mimicked termite behaviour to develop an algorithm which structurally optimises and appraises the manufacturability of AM parts. An algorithm which optimises structurally without influence from nature is not biomimetic.

Although this term is not used in the following chapters of this thesis, it is important to understand the difference to avoid confusion in the future.

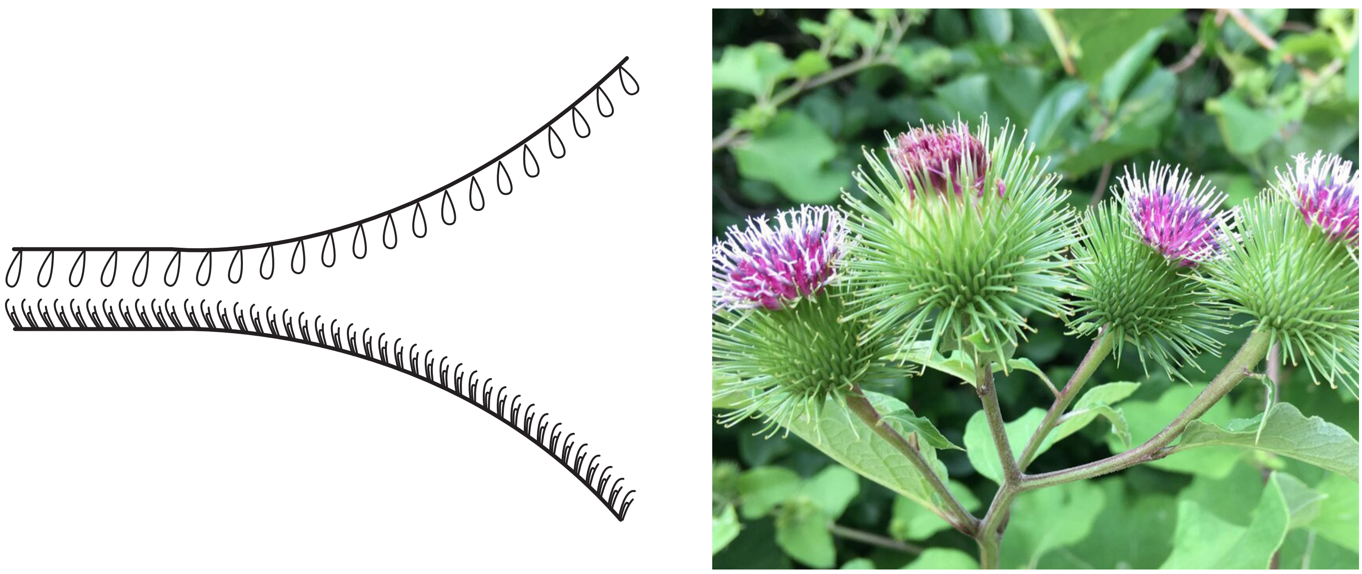

Figure 13: Biomimicry of Velcro(left) and Burdock(right)[26]

Chapter 4

Additive manufacturing

In the last chapter, I explained what generative design is and the differences between generative design, topology optimisation and biomimicry. In this chapter, I will move on to additive manufacturing and focus on fused deposition modelling, a method within AM. I will explain the differences between FMD and AM, how an FDM printer works and how designers can influence the results of FDM products. I will end this chapter with a set of common design rules for FDM which designers need to remember when analysing generative designs.

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4.1. Additive manufacturing

Additive manufacturing, also known as rapid prototyping[12] or 3D printing[9, 11], is a manufacturing method that takes data from a CAD model and builds the physical representation by adding layer-upon-layer of material. It can utilise a wide variety of materials to produce complex shapes[11] using physical or chemical phenomena[12].

AM is different from traditional subtractive manufacturing processes. For example, it is in direct contrast with machining that employs selective material removal[12] such as milling, turning or drilling, as opposed to adding material. It has various advantages and disadvantages compared to the more traditional manufacturing methods. The most general advantages and disadvantages of AM are shown in Table 3.

4.1.1. AM processes

As mentioned in Chapter 1, a range of seven printing process groups exists in AM. They each contain several technologies or methods with their own strengths and limitations. These groups are powder bed fusion, vat polymerisation, material jetting, binder jetting, sheet lamination, directed energy deposition and material extrusion[11]. Each group contains several methods with their own strengths and downsides. The groups with corresponding methods and companies are shown in Figure 14.

Each printing process has its use case and it has allowed businesses to produce new and alternative designs. All printing processes show promising applications[9] and could have added value for SME's in the manufacturing business. Unfortunately, a variety of methods are not economically feasible for SME's due to material costs or production size[9].

The reason why CAD2M invested in FDM, a sub-process of material extrusion, is because it is cheaper, requires less post-processing and its an entry-level product. It is wise to have some prior knowledge of AM before investing in expensive metal 3D printers. This is necessary to prevent wasting expensive resources. FDM is a logical first investment for SME's to acquaint themselves with the method. Therefore, CAD2M and this thesis focus on FDM printers.

Advantages	Disadvantages
Short throughput time[9, 12]	Difficult to achieve economies of scale[9, 11]
Can economically produce small quantities[9, 11]	Time-consuming [9, 12]
Wide range of materials[11, 12]	Variance in geometric tolerance among techniques[11]
Complex shapes[9, 11, 12]	Post-processing[9, 11, 12]
No special tools[12]	Lower surface quality[11]
Multi-material and multi-colour [12]	Lower accuracy[9, 11, 12]
Available for individuals[9, 11]	
Less waste material[9]	
Fully assembled parts[11]	

Table 3: General advantages and disadvantages of AM

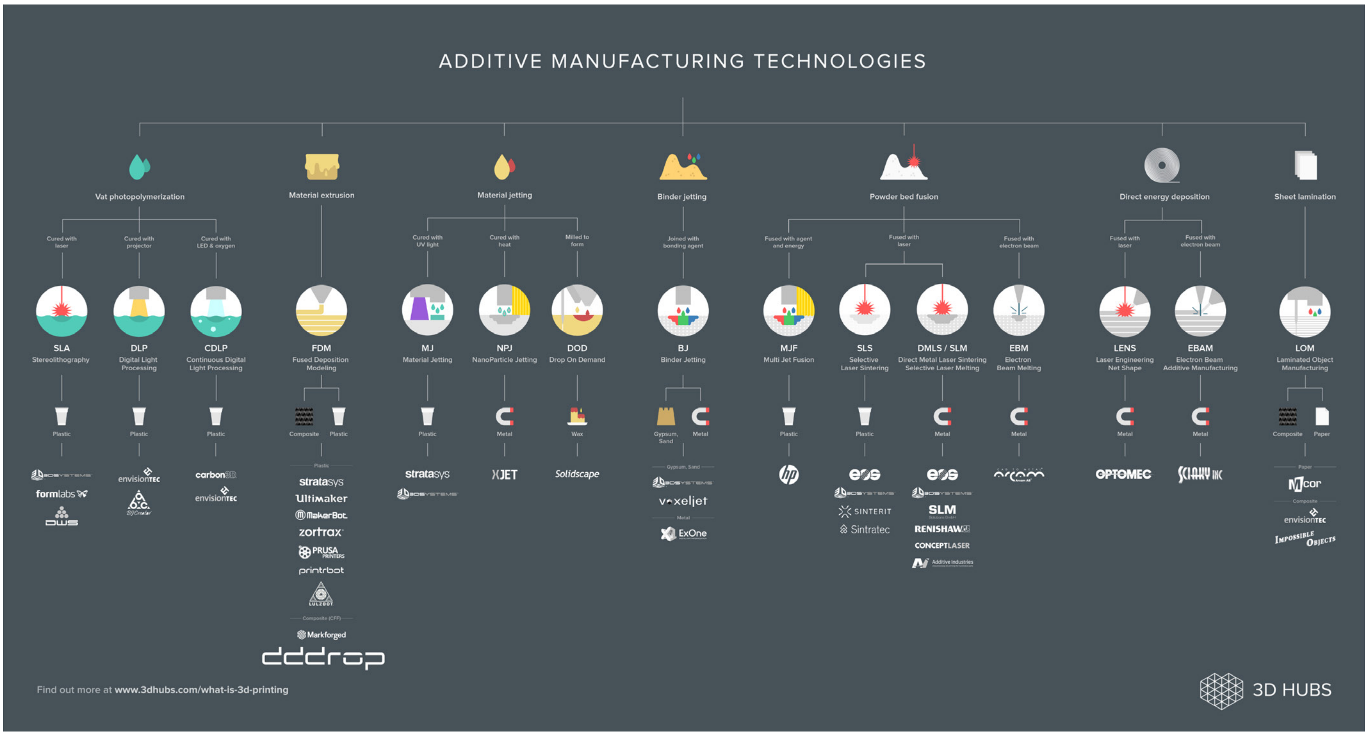

Figure 14: All AM technologies and companies[28]

4.2. What is Fused Deposition Modeling?

FDM is a sub-process of material extrusion. Material extrusion is defined as an AM process which extrudes material through a nozzle onto a build platform[29]. FDM deposits a layer of viscous material upon another layer of material. Due to the viscous state of the warmed-up material, it adheres together and when cooled down forms a physical product.

4.2.1. From geometric model to the physical world

Before the printing process can start, a CAD file needs to be translated. This file needs to go through a series of steps to become a physical product. Ahn et al.[30] describe these steps of the FDM process clearly and in detail. A basic representation of these steps is shown in Figure 15.

First, a solid geometric model (CAD model) is made by a designer or engineer. This model is exported into the STL (Standard Tessellation Language) format which is a geometric representation of the model with triangles. This file is imported into a slicer which can divide the model into thin slices which represent the 2D layers the model is built upon. The slicer will generate tool paths into machine language, also known as G-code, for the FDM printer. This machine language is then transferred to the FDM printer and it can begin producing the physical product. The extrusion nozzle starts depositing material layer by layer until eventually, the accumulation of layers represents the physical 3D model. Lastly, the physical model might need surface treatment to soften the layer transitions or to remove support material. This is an optional step in the process and depends on the design of the model and eventual wishes of the user.

The actual steps made by the computer are in reality more extensive but this is a basic representation of the whole process. The process shown in Figure 15 is also applicable to other AM methods in general, albeit with some changes.

4.2.2. FDM printers

Figure 16 illustrates the very basics of the layout of an FDM printer. A carriage moves the printing head over the x- and y-axis. The printing head contains a filament, often a thermoplastic, which is pressed through the extrusion nozzle using feeders. This filament is warmed up with a heating element so it transforms from a solid to a viscous state. FDM needs a material which will be viscous when hot so it will stick onto the build plate and other deposited material[12]. In theory, any thermoplastic can be used[12] and is what most companies prefer for FDM. The extrusion nozzle deposits the viscous material onto the build platform. When the material cools down, it will harden and become solid again. If a layer is finished, the build platform is lowered and the printing head starts the next layer.

It is important to realise that all FDM printers are based on the same principle as explained in the paragraph above. A variety of different FDM printers exist in alternative compositions with different parts and configurations. For example, some FDM printers have a fixed build platform and the carriage controls the z-axis as well as the x- and y-axis. Nonetheless, the modus operandi of all machines is unchanged.

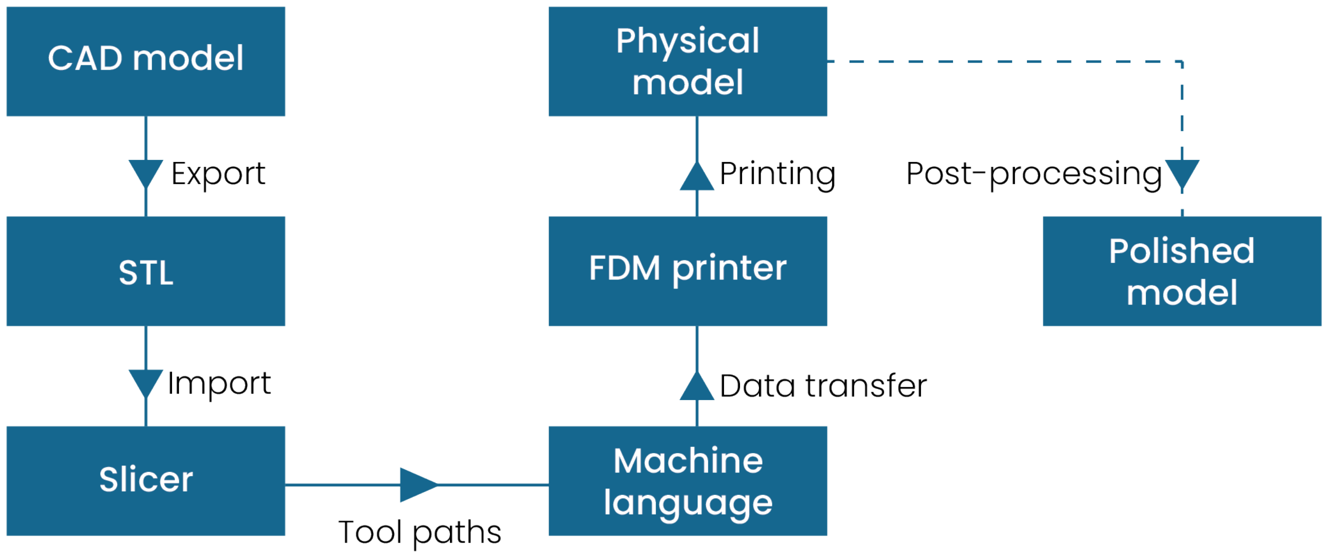

Figure 15: Basic representation of the FDM process

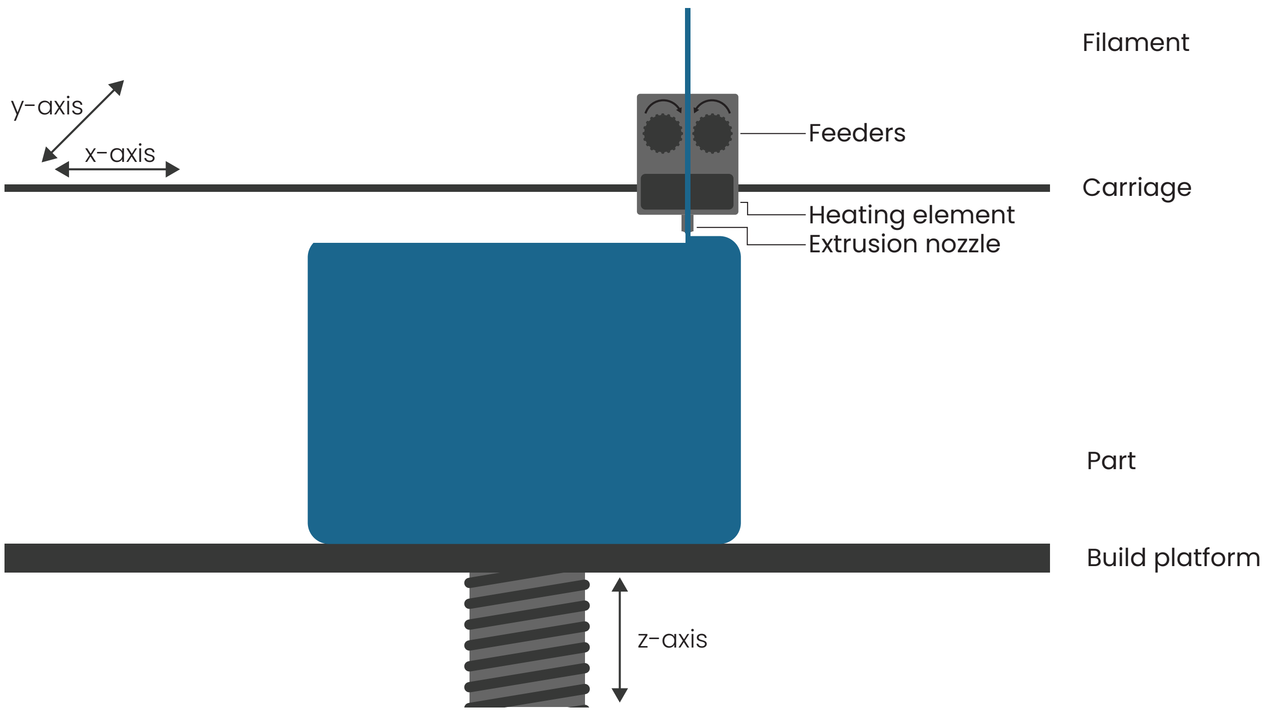

Figure 16: The basic components of an FDM printer

4.2.3. Important factors in FDM

According to Vaneker[29], there are certain criteria which need to be fulfilled in material extrusion to be able to make a sturdy part:

1. *The feeder should give constant pressure in the nozzle for constant outflow.*
2. *The nozzle speed relative to the build platform should be constant.*
3. *The material should be viscous in the extrusion nozzle.*
4. *After extrusion, the material should solidify fast so it will retain its shape.*
5. *The material must bound to already deposited material to form a solid structure.*

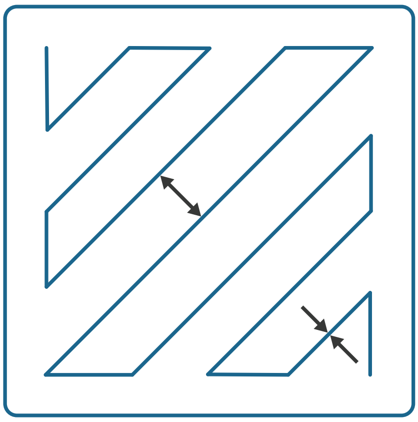

Figure 17: Air gap and raster width explained

These are the very basic characteristics needed to be able to produce parts via FDM. However, there are other parameters which can influence the quality of the part and its mechanical properties. According to Sood et al.[31] there are five control factors which have the largest influence on the strength of the part which are:

1. *Build orientation*
2. *Layer thickness*
3. *Raster angle*
4. *Raster width*
5. *Air gap*

The build orientation means the direction concerning the x-, y- and z-axis in which the part is printed on the build platform. The layer thickness refers to the thickness of each layer. The raster angle is the angle between the path of the nozzle and the x-axis of the building platform[32]. The raster width, sometimes also referred to as road width, is the width of the path related to the tip size of the extrusion nozzle[33]. The air gap is the gap between two roads of deposited material. Figure 17 illustrates the difference between the air gap and raster width.

These parameters can be optimised depending on the specific FDM printer and the chosen material. While the criteria defined by Vaneker[29] are mostly dependent on the hardware and material, the parameters by Sood et al.[31] can be adjusted in the slicer software.

Sood et al.[31] have defined the five factors which have the biggest influence on the final result. However, slicer software contains many more parameters which can be adjusted. Each parameter can influence the final result. Which is why 3D printer companies such as Dddrop have determined the ideal settings for their printer in combination with a certain material. Companies can download these settings and insert them in their slicer software. This can reduce the amount of time and error because companies do not need to experiment with settings and can immediately start printing with an STL-file.

In summary, slicer software contains various settings and parameters which can be adjusted such as the air gap and layer thickness. However, while a compromise can be made in the strength and precision of the part and the speed at which it is produced, eventually the optimum settings are achieved. The only other changes which can be made that have a big impact on the strength of the part is the design and the designer's intention.

4.3. Design for additive manufacturing

Generated designs form very organic shapes and structures which can cause complications during the printing process in FDM. AM methods already have an advantage in generative designs compared to traditional methods because of the layer-for-layer method which removes the geometric complexity[22]. The structure of the 3D model can have a significant impact on the final physical product.

AM is a process which comes with its own challenges. Although it allows for geometric complexity, there are some considerations to take into account when designing the geometric models. Design for Additive Manufacturing (DfAM) is a method in which designers try to create products which take advantage of the unique capabilities of AM[34]. Furthermore, it respects the manufacturing restrictions of AM.

Diegel et al.[34] state that DfAM is a thought process in which designers cannot simply follow design rules to produce a perfect design. Decisions are thought out carefully and compromises have to be made in DfAM. Currently, most engineers try to re-design current products instead of utilising the full benefits of the AM process. DfAM has two basic components[35]:

1. *Maximise the benefit outside the production phase.*
2. *Minimise the drawback and limitations related to the actual additive manufacturing process.*

DfAM is more about considering the benefits of AM products in comparison to traditionally manufactured products. Therefore, it has several guidelines to follow when designing for AM. These guidelines need to be taken into consideration for every AM process[34-36].

- *Use the advantages of additive manufacturing processes.*
- *Do not build or redesign parts which are made for traditional manufacturing.*
- *Merge parts in one assembly by integrating functions.*
- *Optimise parts by reducing weight while keeping strength.*

4.3.1. Design rules for FDM and generative design

DfAM is very important when designers work with generated designs. Due to the complex results of generated design, some generated designs are very difficult to produce. With DfAM in mind, designers can already control parameter settings in CAD software beforehand to minimalise production mistakes.

Few software packages incorporate the complete restrictions of the manufacturing process of AM. Furthermore, the restrictions are generalised and often do not include specific FDM restrictions. Designers or engineers need to consider several challenges when adjusting generated designs to make it suitable for FDM printing.

Companies and individuals have tried to form design rules which need to be followed to reduce faults during the printing process. These rules need to be applied to the CAD models of generated designs before 3D printing with FDM machines.

In the following sections, the most important design rules for FDM are given which improve the stability and strength of a printed part. Several sources were used for information and this information was combined to form the following design rules[34-38].

4.3.1.1. Overhang

Each layer of material is dependent on the layer of material below it. Material needs support because it cannot be deposited into the air without falling. Thus, when the angle between layers is too steep, support material is necessary to prevent a warped or transformed surface and proper geometry, see Figure 18. Thumb of rule is to never exceed an angle of 45° for a sturdy part and better surface finish.

Due to the nature of generative design, a variety of different angles occur in products. Engineers and designers should watch out that these angles are not too steep. Support material can resolve the issue but will result in rougher surface finish, more post-processing time and may be difficult to remove completely depending on the material surrounding it. For example, see Figure 56 in which support material is impossible to remove.

4.3.1.2. Bridging

Bridging is similar to overhang but instead of printing at an angle, a bridge is made between two gaps of material with no material underneath, see Figure 19. Generated designs may have some bridges which can cause problems such as sagging of the material. Support material is necessary after 10mm of bridging and recommended after 5mm. But this results in more post-processing and a rougher surface finish.

It is advised that designers inspect their generated designs to determine if all bridges are less than 5mm. If not, more solid material needs to be added to the design to get better and more reliable results.

4.3.1.3. Warping

If a design contains a large flat surface on the printing bed, warping can occur as seen in Figure 20. Physical changes in the characteristics of the material occur due to heating, cooling and compression of material. Eventually, the product can change shape and curl away from the printing bed. Certain design adjustments to generated designs can prevent warping.

First of all, a brim or raft can be added in the slicing software. A brim or raft is a layer of material added to the bottom of the product which can be removed later on. These help with adhesion of the bottom layer to the printing bed.

Furthermore, helper disks as shown in Figure 21 can prevent warping altogether[39]. Helper desks are small thin circles of material added to the corners of the bottom layer of the material. This helps with adhesion to the build plate. However, it does require more design work, more post-processing and the product has corners with a rougher surface finish because the disks need to be removed after printing.

4.3.1.4. Corners

The extrusion nozzle of FDM printers are circular thus perfect rectangular corners are impossible to produce. Also, compression of the material results in an 'elephant's foot' when trying to make square corners. Due to the weight of the material, a compression occurs at the lowest part of the material which creates the elephant's foot as seen in Figure 22.

An easy solution is to apply minuscule chamfers or fillets with a very small radius at all bottom corners which counteracts the compression. However, this does reduce the adhesion of the material to the build plate which may cause warping.

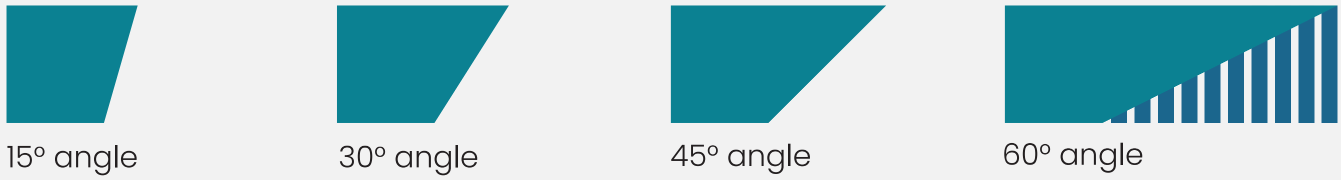

Figure 18: Overhang

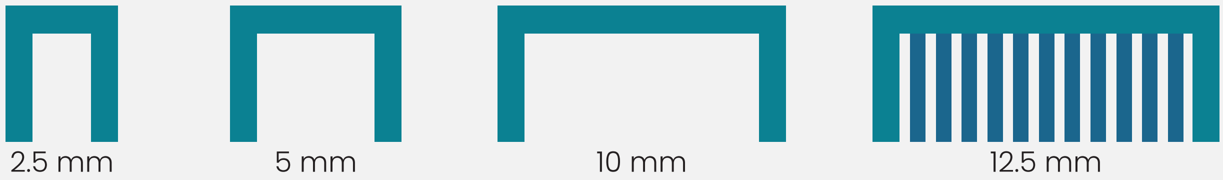

Figure 19: Overhang

Figure 20: Warping

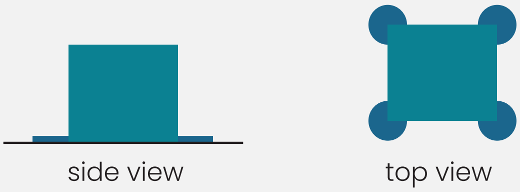

Figure 21: Helper disks

Figure 22: Corners

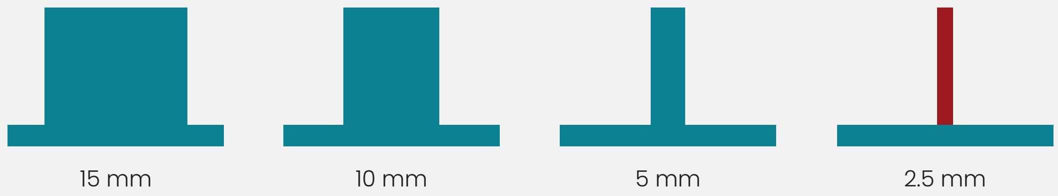

Figure 23: Vertical pin

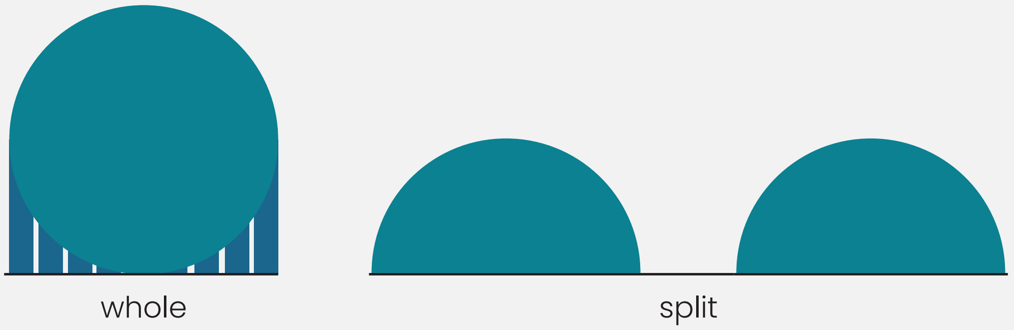

Figure 24: Splitting

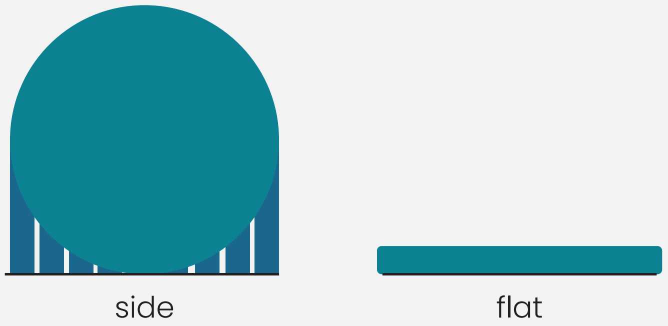

Figure 25: Build orientation

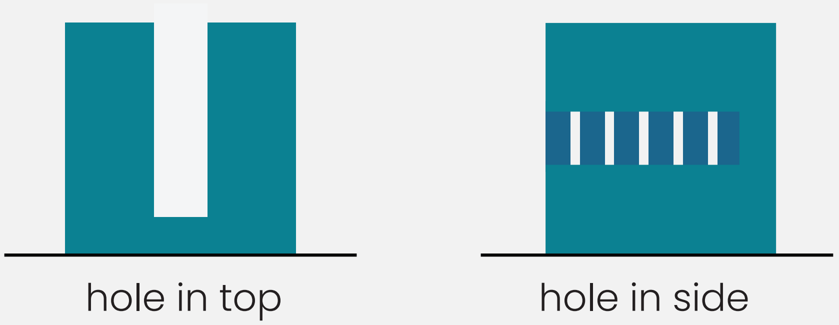

Figure 26: Hole orientation

4.3.1.5. Vertical pins

A generated design can be asked to create a vertical pin which is often needed to make a physical connection to another part. Larger pins with 100% infill are strong enough, but smaller pins (less than 5 mm) do not have infill and are only printed with a perimeter. These small pins are prone to break and are difficult to print correctly, see Figure 23.

Fillets can be added to the base of vertical pins to increase the strength. However, if high strength is required it is advised to maybe remove the printed vertical pin and add a separate metal pin after printing instead.

4.3.1.6. Splitting

Support material is a necessary evil which sometimes cannot be removed. One trick which software does not use is to split one part into two or multiple parts, see Figure 24. This can remove support material altogether. The disadvantage is that the two separate parts need to be glued or screwed together afterwards. More steps are required and the part may be less strong altogether.

4.3.1.7. Product orientation

Generative design software does not consider build- and hole orientation as shown in Figure 25 and 26. Adjusting orientation can prevent usage of support material. Designers need to recall the orientation of certain product properties when inserting design requirements into the software. For example, required drill holes need to be added vertically instead of horizontally to prevent support material.

PART

Research methods

Chapter 5
Methodology

The methods used during this thesis and the following chapters are explained in this chapter. The scope in addition to certain complications encountered during the research is discussed in further detail in this chapter.

Chapter 6
Literature research

A literature research was conducted in order to investigate the current state of the art of generative design. This chapter highlights certain aspects of the literature and ends with a few statements about the current state of generative design.

Chapter 7
Market research

Market research was done by interviewing employees of Dddrop 3D printers, affiliated customers and executives from Dassault Systèmes. The focus was on SME's and their view on incorporating generative design in their current processes.

Chapter 8
Software research

CAD software packages by Dassault Systèmes are analysed in this chapter to grasp the difficulty of generative design. A few competitors were analysed with an online desk research and the software was compared. The chapter ends with a conclusion on the general status of generative design in software.

Chapter 5

Methodology

In this chapter, I will dive deeper into the methodology of this thesis. The following sections I will talk about the methods used in this thesis to answer the research question. More importantly, I will explain why certain choices were made and why certain limitations hindered my progress. I will begin by giving the scope of my thesis and emphasising the research outline. Lastly, I will hold a short discussion about the reliability and validity of this research.

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5.1. Scope

This thesis was made possible by the cooperation of the company CAD2M. As mentioned before, they are an official reseller of CAD software that is developed by Dassault Systèmes. The decision was made that all software in this research is professional CAD software which is owned by Dassault Systèmes. Dassault has a large market share as seen in FIgures 27-29. The company is large enough that it will represent a similar state of progress in generative design compared to its competitors.

Still, parties such as Siemens and Autodesk might have software which is better suited or more progressive regarding generative design. Due to a paywall or limited demo time, the author was unable to test these software packages so an online desk research was done instead.

Smaller CAD software packages or add-ons were disregarded for various reasons. SME's prefer to use more well-known software because it is an industry-standard, makes communication with clients easier and reduces complexity, see Chapter 7.

As for hardware, CAD2M develops and builds its own line of 3D printers with their sister company Dddrop 3D printers. The decision was made to do all tests using their Dddrop Evo Twin printer. At the time of writing, Dddrop just released their new FDM 3D printer called the Rapid One. However, it was the first version and thus changes will be made in the future. The Evo Twin is already fully developed and so a stable version to test with. The specifics of the Evo Twin are given in Appendix A.

The coverage of this study is limited to the geographical location of the Benelux which are the countries of Belgium, The Netherlands and Luxembourg. This decision was made because CAD2M focuses on this region and the technological capabilities of these countries are not so different[40] that the results might be inaccessible for one of them. While the results can also be used by SME's in other countries, they might not have the technology available such as FDM 3D printers or CAD software.

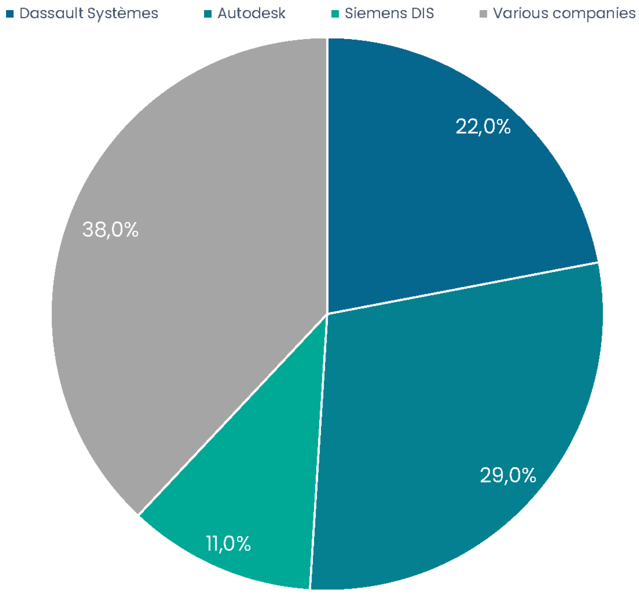

Figure 27: CAD company market share in 2020[41]

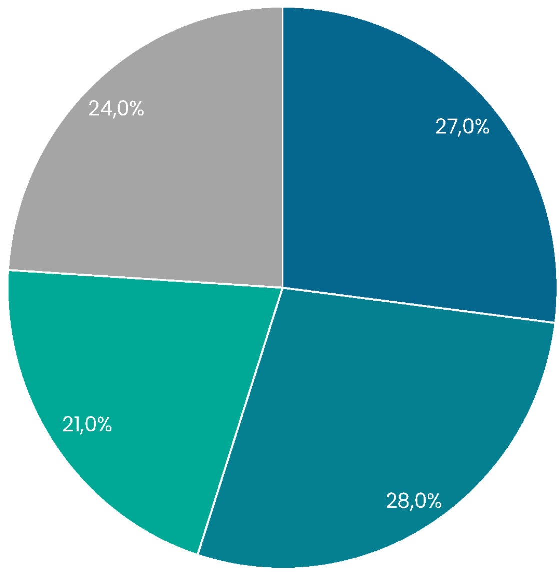

Figure 28: CAD software in use per company 2020[43]

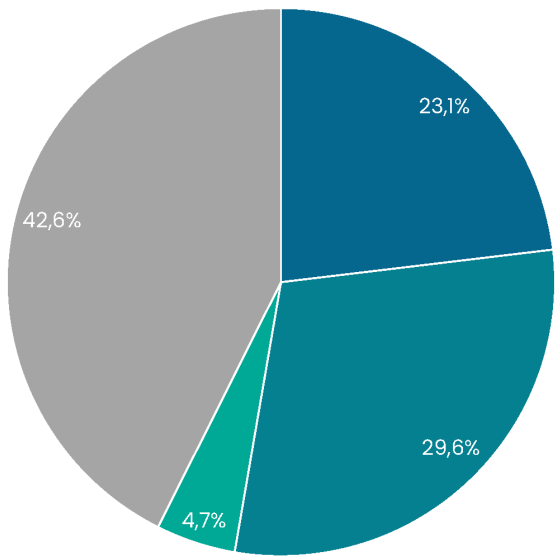

Figure 29: CAD software market share 2016[42]

5.2. Research question

The goal of this thesis was to see if the bridge between SME's and generative design can be gapped. As mentioned in Chapter 3, actually producing reliable parts using generative design is difficult due to costs, lack of available technology and non-optimum production methods. Moreover, the novelty of the area results in misnomers and confusion among interested parties. For example, the term generative design is often confused with topology optimisation.

How to bridge the gap between SME's and generative design with a set of design rules in order to produce reliable generated designs with FDM printers?

5.3. Research outline

This thesis will have a theoretical and practical deliverable. First, the theoretical deliverable will be an evaluation of the current state of generative design. It will discuss its shortcomings, misconceptions and recommendations for the future to implement the method in workflows of SME's. This theoretical deliverable can be taken as a basis for future research in generative design.

Secondly, the practical deliverable will be focused on SME's of CAD2M clients. It will be a deliverable containing summarised information about generative design, why companies should use it and tips and tricks on how to produce generated designs immediately. It will focus on introducing the concept of generative design and promoting its potential benefits. Its exact form will be discussed and eventually executed in cooperation with CAD2M.

The results of this study might become redundant in the upcoming years due to advancements in technology. However, the added value proposition of this research is that in the meantime, SME's can start learning about generative design and experiment with 3D printed generated designs to prepare for the future of engineering methods.

5.4. Research methods

A variety of different qualitative research methods are used to get the most comprehensive view of the current state of generative design. The methods used are literature research, interviews with clients and stakeholders, software research and online desk research.

5.4.1. Literature research

Extensive literature research will provide sufficient background information about relevant studies regarding generative design. This is necessary to acquire enough knowledge to give an insight into the current state of the art of generative design.

5.4.2. Interviews

A series of semi-structured interviews were held with CAD2M employees to get to the core of their assignment and problems their clients face. Several of their clients were also interviewed to see if know what generative design is and if it is relevant for them. The structure of these interviews can be found in Appendix D.

The number of interviews was reduced and held over the telephone due to the COVID-19 pandemic that was ongoing during this thesis. Due to the pandemic, face to face meetings was not possible. In response, interview questions were reduced to very basic questions due to personal experience of the CAD2M sales team. According to them, clients are less willing to answer questions if interviews take up too much time over the telephone. The amount of interviews is also very small due to unwillingness of companies doing interviews over the phone.

The decision was made to hold interviews instead of spreading a survey among clients. On paper, companies are always willing to indicate they want innovation but in reality, changing their methods is more difficult. Interviews can give a better insight into the problems companies encounter which is why interviews were the preferred research method.

5.5.1. Software research

CAD applications and software by Dassault will be tested to see if they have true generative design capabilities. These will be ranked on several aspects to determine the potential uses of the software.

5.5.2. Online desk research

Competitive software of Dassault Systèmes is very secretive about their current state of CAD software. Software research was not feasible so online desk research with videos, tutorials and online articles were used to achieve a representation of their generative design integrations.

5.5. Reliability and validity

To get qualitative unbiased data, the interviews were semi-structured. The questions were expressed in such a degree that it would not influence the answers of the interviewees. Other quantitative data which were acquired such as the date for the software research could be biased. The experience of the software probably differs per person.

Furthermore, the documentation of the less well-known software packages was very limited. It might be that several features in the software have been missed because it was unknown to the author.

Chapter 6

Literature research

This chapter is where I dive deep into the current state of the art of generative design. I will talk about the first generative designs and look into the current problems that research into generative design faces. I will end this chapter with a summation of statements that can be made about the current state of generative design.

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6.1. History of generative design

It is unclear when exactly the term generative design was first introduced. But in the early 1970s, John Frazer became a pioneer and developed one of the first generative design systems[3]. At the time, the term generative design did not yet exist and Frazer referred to his work as the 'concept seeding approach'. He developed the Reptile System which was one of the first programmes that utilised a form of generative design. His goal was to prove to architects, fixed in their ways and methods, that computers and software can aid the design process[44].

A simplified explanation is that his system starts with a seed which contains a number of structural units, as seen in Figure 30, in different configurations, see Figure 31. This seed varies each time in configuration when it is reset. A programme generates a 'building plan' using the seed and grows by looking at the orientation and location of adjacent units. A minimal number of requirements could be given as input such as maximum size of the building plan.

This programme was able to develop different variants of a building using one seed[45]. Figure 32 shows a building plan generated using a 'star' seed developed by Frazer. This was very impressive at the time seeing as this was never done before. Furthermore, Frazer had to share the only computer in the University of Cambrige that was able to make these kinds of graphics at the time with other researchers[45].

The Reptile System demonstrated the feasibility of the technique and the possibilities with limited resources. The drawback was the minimal number of geometric components that were repeated in a single enclosed form. The next step was incorporating reactions and evolutions by evaluating the design after each step.

Generative design has made tremendous progressive steps since then regarding academic research and even has entered the commercial market. The fact that AM is nowadays a viable option for manufacturing has contributed to its progression. Academic literature shows that research is progressing in various facets.

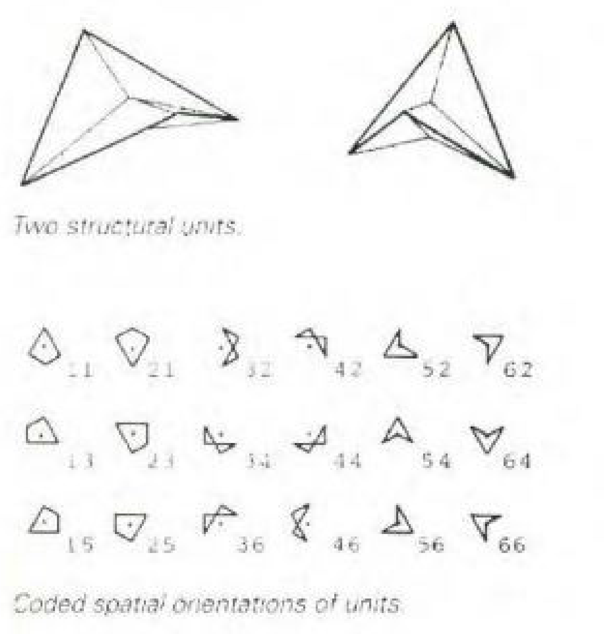

Figure 30: Structural units[24]

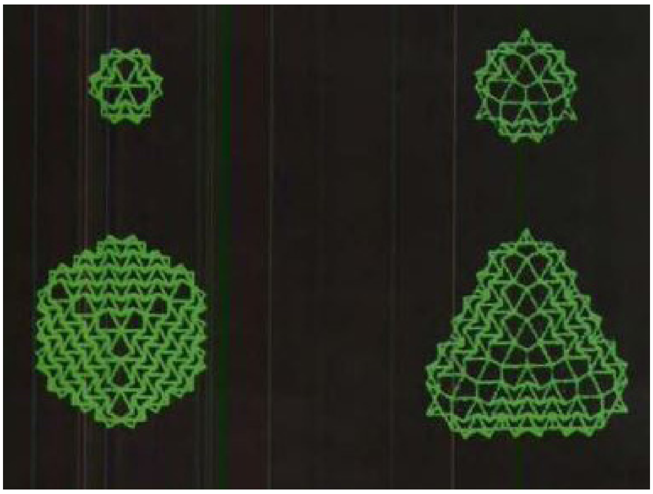

Figure 31: Different seed configurations[24]

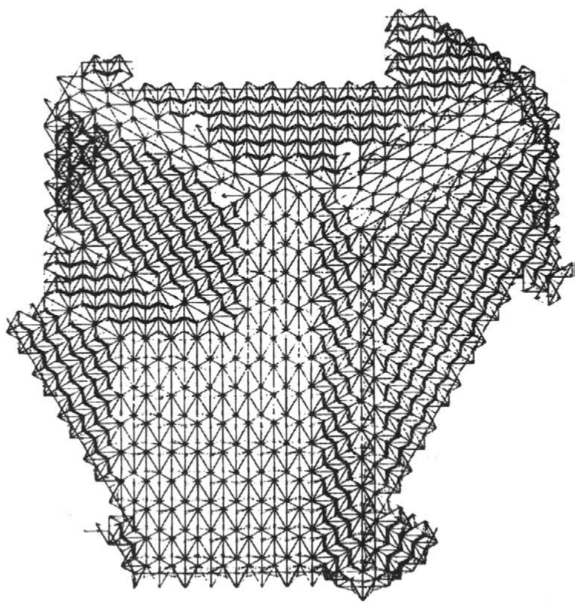

Figure 32: The plan of a building generated from a star seed by Frazer[45]

6.2. Insertion of correct parameters

A recurring problem with generative design is the difficulty inserting the correct parameters. For example, Caldas[46] researched the GENE_ARCH system which is an evolution-based generative design system for the AEC (Architecture, engineering and construction) industry that allows architects to define goals for a building's performance. This could be requirements such as energy efficiency as shown in Figure 33. GENE_ARCH can generate multiple building designs, including characteristics like spatial layout, construction materials and windows. The objective of Caldas was to look at the current limitations of the system. These are also relevant for generative design methods applied in other practices.

One of Caldas main conclusions is the difficulty of problem presentation[46]. Wherein the designer cannot or finds it difficult to define the restrictions and requirements of the desired product. The given requirements by the designer need to be exact. Otherwise, the generative design model might allow emerging of undesired design characteristics[46]. Liu et al. highlight this problem when combining generative design with AM. Incorrect parameters may result in reduced strength of parts[22].

Similar results were given by research work carried out by Daher et al.[47] or Painting with Light developed by Caldas et al.[48]. Both are analysing generative design and learning about possible implementations for the architecture and urban planning industry. Daher investigated if generative design can be a potential application to assist in humanitarian aid. Painting with Light is an interactive application in which architects can draw in a model what the daylight level in certain places should be. A generative design model would calculate the shape of the roof and its windows. Both Caldas et al. and Daher et al. make statements about the current difficulty of entering correct and complete parameters into their respective systems. This is a problem that is not solved yet.

Due to the difficulty of inserting correct parameters, researchers have been busy incorporating easer design processes. One of the first was Shea et al.[7] who combined a generative structural design system with an associative modelling system. A structural design system involves the conception of forms that meet several goals such as aesthetic or behavioural goals[49] while associative modelling is, very simply defined as, using geometric constraints[50]. Thus, Shea et al. tried to broaden the number of parameters for designers to specify their design intent, see Figure 34 for the difference.

The research by Shea et al. was published in 2005 and is outdated because such systems are now integrated into commercial CAD software. However, Shea et al. had some interesting thoughts about future work. First, investigations are needed in a system that could aid in negotiations when working in a multi-disciplinary design team. A next challenge that needs to be conquered according to Shea et al. is developing a system that designers actually want to use. These suggestions for future work are still relevant because both are not yet implemented.

Figure 33: On the left, different buildings. On the right, the same buildings optimised by GENE_ARCH for energy consumption[46]

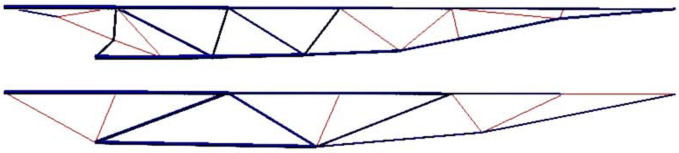

Figure 34: Two cantilever truss alternatives that illustrate design variation if constraints are relaxed(top) or more conventional(bottom)[7]

6.3. Aesthetic considerations

The involvement of aesthetics in designs is often forgotten when discussing generative design. The production of optimal solutions and engineering performance has a higher priority. The organic forms and shapes are considered to be good enough concerning aesthetics because it is unlike anything we have ever seen in products. But organic shapes can have undesired compositions as well due to the production method or style of the brand itself.

Oh et al.[18, 51] wanted to present the need for adopting deep learning in generative design and its effectiveness. Deep learning is a sub-category of machine learning in which machines attempt to learn patterns by analysing data. Utilising deep learning, Oh et al. proposed a generative design framework that produces design solutions which are optimised for engineering performance as well as aesthetics. Unfortunately, the proposed framework was only successful for 2D design space and pixelated images as shown in Figure 35. It is not yet suited for 3D applications, so it still cannot be used for practical purposes in real-life applications.

Gunpinar[52] developed a generative design method which involves using particle tracing algorithms. Gunpinar's algorithm tries to produce as many shape variations as possible which will result in products which will attract consumers. His algorithm worked in three steps. First, a shape space is defined which is the space that can be filled. Secondly, their particle tracing programme with specific rules finds feasible shapes. Lastly, another algorithm is used to find shape representatives between the particles to fill the shape. Results from the algorithm can be seen in Figure 36. The goal was to see if it was possible to not only develop more aesthetic models but also to see if the models were feasible. After conducting a user study, it was proven that their algorithm develops slightly more pleasing designs than alternative solutions.

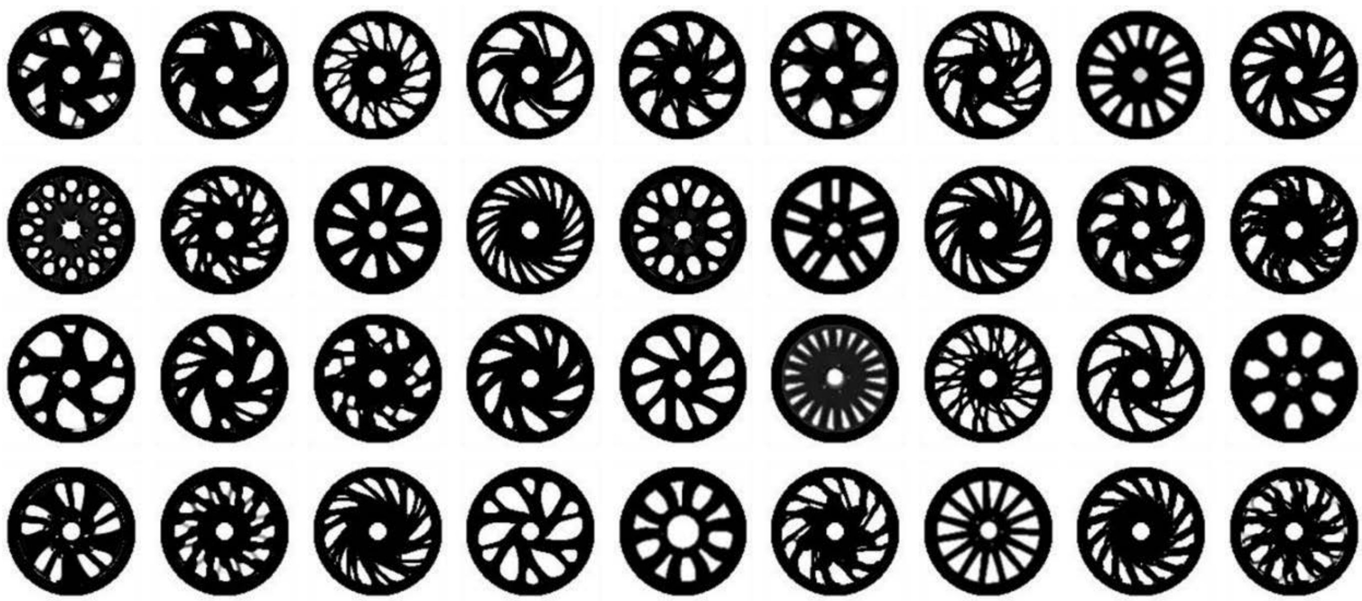

Figure 35: Generated design options of a wheel[18]

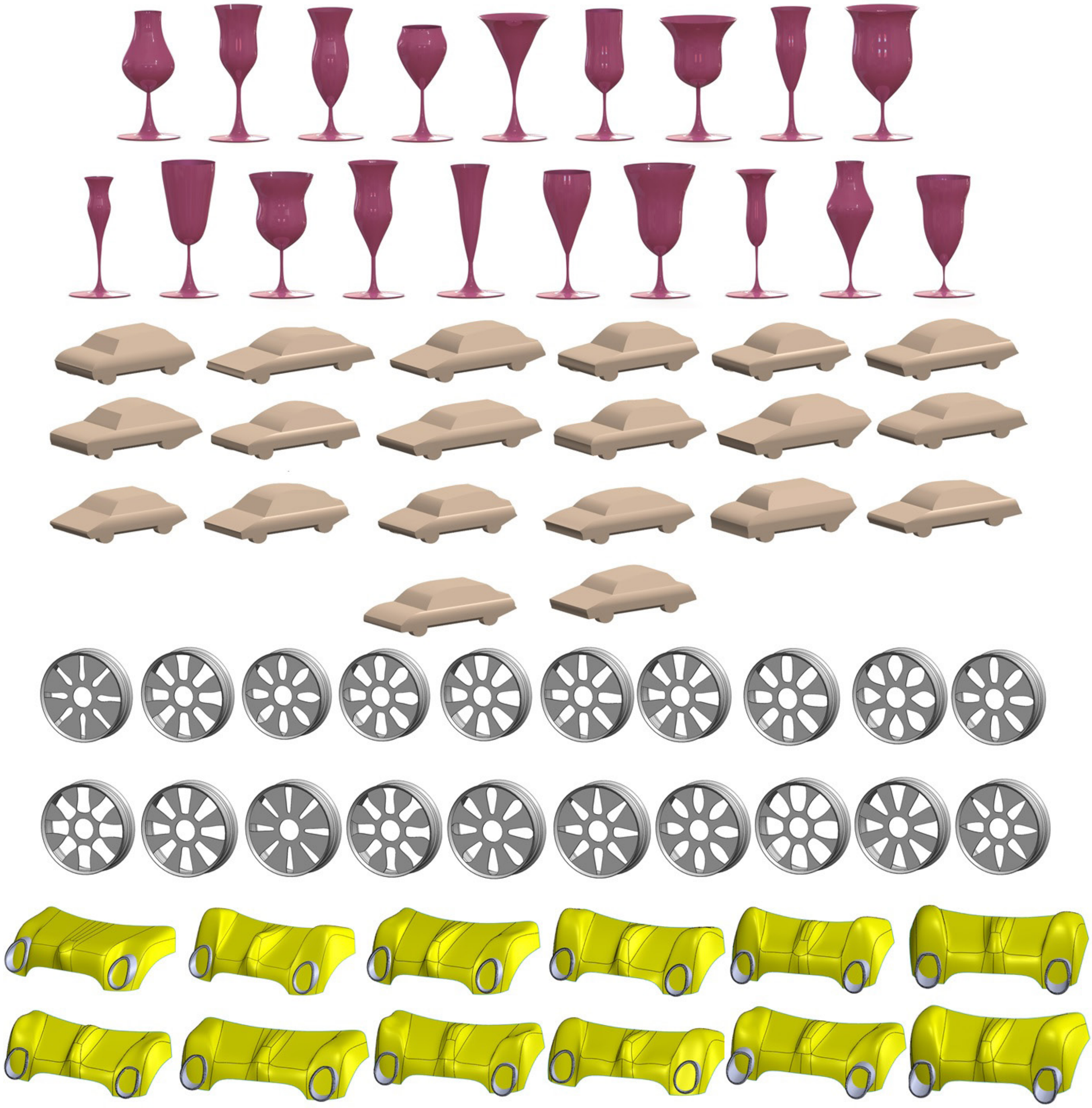

Figure 36: Generated designs of various objects using Gunpinar's algorithm[52]

6.4. Improve structure of CAD models for AM

Several researchers are trying to improve the generative algorithms to improve the structural integrity of additive manufactured designs. Dhokia et al.[6] want to improve current algorithms by looking at how termites build their nest and incorporate their behaviour in an algorithm. This algorithm is capable of designing and appraising the manufacturability of the results for AM. It is capable of developing lighter parts, can be reliably manufactured and does not compromise the required functionality. This results in designs which are structurally sounder and easier to develop without using support material. An example of such a result is given in Figure 37.

Fantini et al.[53] wanted to improve synthetic scaffolds which are used to guide tissue regeneration. A scaffold provides a structural template that can support surrounding tissue by bearing the loads. The cells surrounding the scaffold then have ample time to regenerate in the pores of the scaffold. In combination with AM and a generative design method inspired by Voronoi diagrams, see Figure 38, they were able to mimic scaffolds with the same structure and pores as natural bone. Metal-based Additive Manufacturing methods such as Selective Laser Melting and Electron Beam Melting can be used to produce the scaffolds. The polymer used in bone tissue-engineering is Poly Propylene Fumarate[53] but it is not yet possible to produce these kinds of polymers accurately or clean enough using FDM[54].

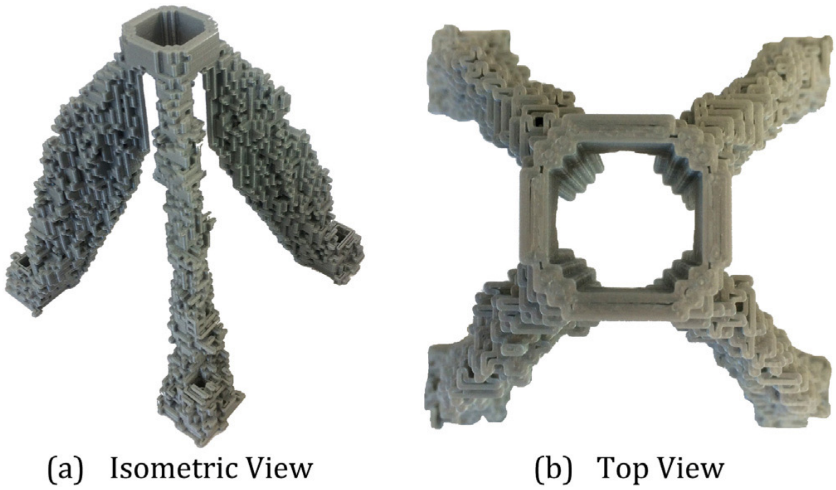

Figure 37: The 60th iteration of the algorithm printed using FDM[6]

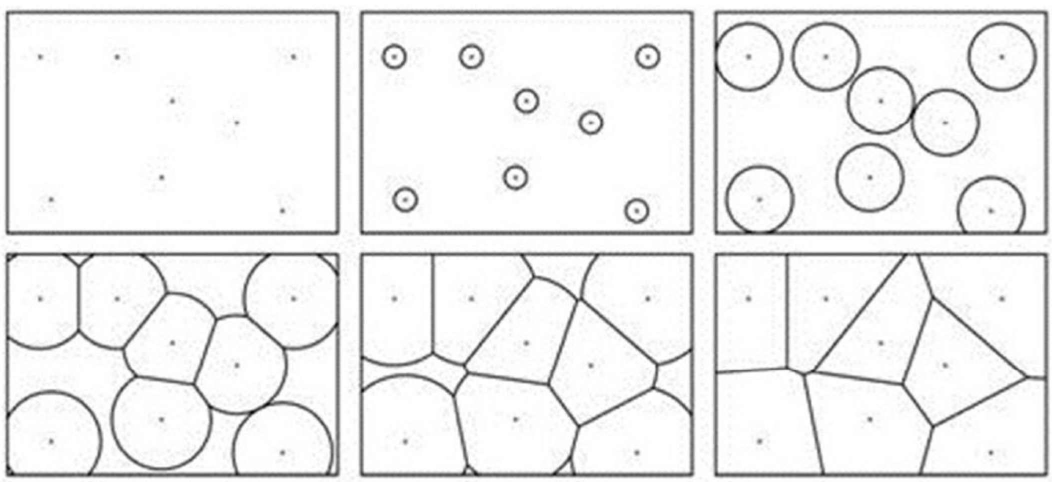

Figure 38: A graphical representation of the formation of a 2D Voronoi diagram[53]. A collection of points randomly distributed in space slowly expand until hitting other regions

6.5. Elimination of designs

Currently, generative design methods are developed enough that it is feasible to use them as datasets. For example, Rodrigues et al.[17] used generative design to produce a dataset of 6010 houses to test which designs had the highest energy consumption when using air-conditioning in Kuwait. Rodrigues et al. show an alternative way of using generative design by applying it as an evaluation tool. However, they concluded that it is laborious and neigh impossible for designers to evaluate six thousand design without assistance.

The Dream Lens system made by Matejka et al. [13] tries to alleviate this problem by providing an overview of all generated designs. It highlights differences in appearance and properties, while encouraging exploration of a variety of 3D models. It also implements a ranking algorithm where users can 'like' or 'dislike' a design by assigning a '+' or '-'. The system then ranks all variations where designs, similar to previously liked designs and dissimilar to disliked designs, get a higher ranking and vice versa. This helps the designer with the elimination progress, especially when there are a lot of variations. Figure 39 shows the top models based upon the ranking. While is it a novel contribution to this area of research[13], it is not yet practically implemented in commercial software.

Gerber et al.[55] combined generative design methodology and a multi-agent system to improve and partially automate architectural designs. Exploration of generative designs which adhere to certain performance criteria would be more accessible using their system. Additionally, the system would help assist by providing geometrical and environmental feedback to help with the selection procedure of designs.

The multi-agent system consisted of four agents which were the generative agent, the simulation agent, the specialist agent and a coordination agent. The generative agent contained an algorithm which took the preferences of the designer and geometric constraints and converted it into a design. The simulation agent converted the design to comply more with user preferences while the specialist agent performs environmental analyses. The coordination agent is responsible for managing the communication between all agents.

The results proved that such a system can provide design solutions to designers which would not be possible when done manually. It also helps designers select more optimal designs by providing immediate feedback on the generated design solutions.

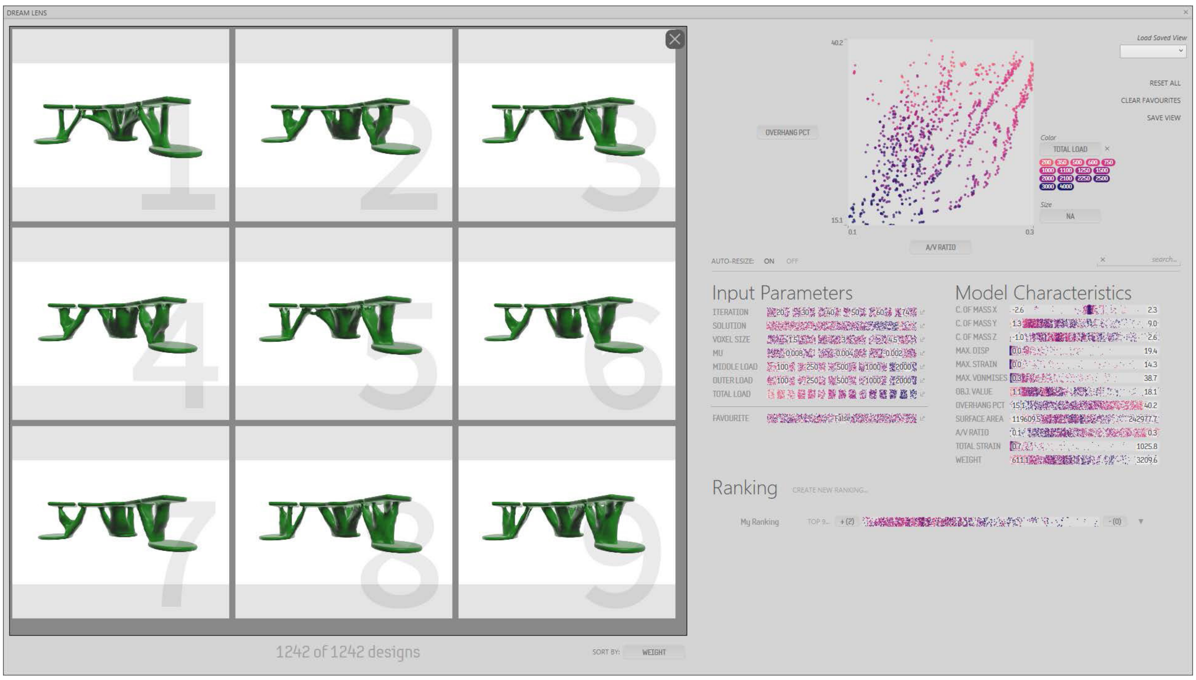

Figure 39: Top nine results for a desk design based on the ranking[13]

Due to the difficulty of inserting correct parameters, researchers are busy trying to improve the parametric design process in order to make the elimination process easier. Nagy et al.[56] explain that the basic parametric model needs to be extended to achieve that goal. First, specific metrics are needed related to the goal which help the software decide which designs are better. Secondly, a search algorithm that can tinker with input parameters of the model while simultaneously processing feedback from the metrics is necessary.

Nagy et al. developed a generative design work flow which incorporates those two necessities. Its goal is to "create a more dynamic and collaborative interaction between computer design software and human designers"[56].

Their system was able to use the metrics, as seen in Figure 40, and give each generated design a score per rank. Additionally, the system was also able to analyse the trade-off between metrics. The system would provide the designer with a set of designs which were 'statistically dominant' in addition to designs with different scores along the trade-off graph. This would assist the designer in analysing the effects of each metric.

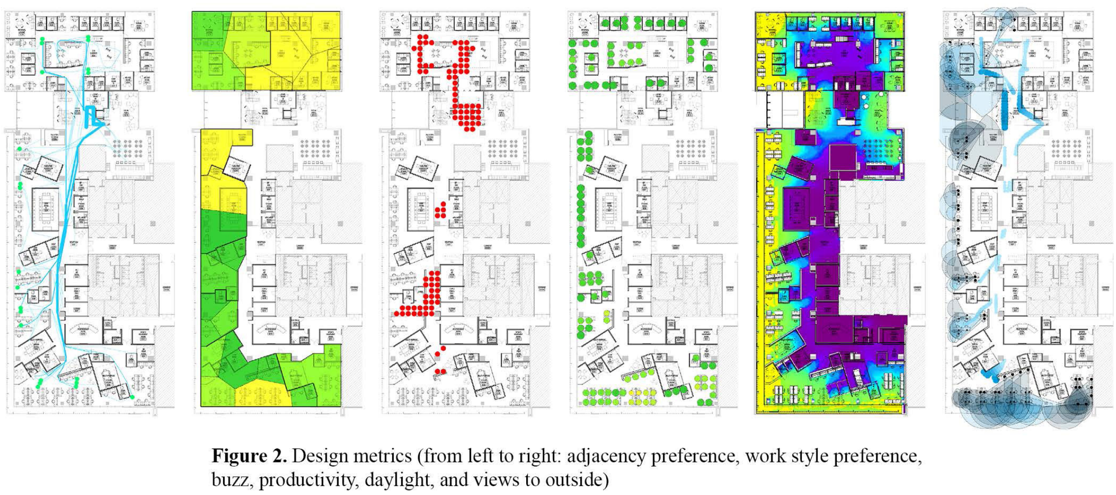

Figure 40: Improved design metrics to optimise the generated design solutions for an office space. From left to right: Adjacency preference, work style preference, buzz, productivity, daylight and views to outside[56].

6.6. Design exploration

Generative design is now available to not only researchers but also businesses and individual consumers depending on the provider. A lot of research is done into optimising and improving the software for designers and engineers to improve exploring multiple design variations.

For example, Kazi et al.[4] developed DreamSketch. This product is an interface that allows designers to sketch free-form in a 3D space and provide design context. It allows users to define variables, constraints and other configurations using different colours. Then, a topology optimisation algorithm will produce multiple optimal solutions. The focus of DreamSketch is on exploration and showing the possibilities.

Genoform, developed by Sivam Krish, is software that offers the opportunity of design exploration. It is a stand-alone programme and a compatible plug-in for multiple CAD software programmes[57]. It takes an existing parametric model and it creates random alternatives. Although it has the same goal as DreamSketch, namely exploration of designs, it differs in its approach.

DreamSketch, see Figure 41, takes a sketch by the user with pre-defined constraints and immediately applies these constraints during generating the designs. In contrast, Genoform first creates random alternatives and configurations of the given 3D model. As soon as the designs are created, the designs go through a set of user-defined constraints. Consequently, after this process, the user gets a more varied set of optimal designs compared to DreamSketch.

Design explorations developed by a generative design methodology could have a drawback. Those designs capture shortcomings of already well-designed products made by humans. Caldas mentions it could raise issues of authorship[46]. On the other hand, it could also be seen as a refined feedback tool where multiple generated designs show flaws or solutions for different objectives.

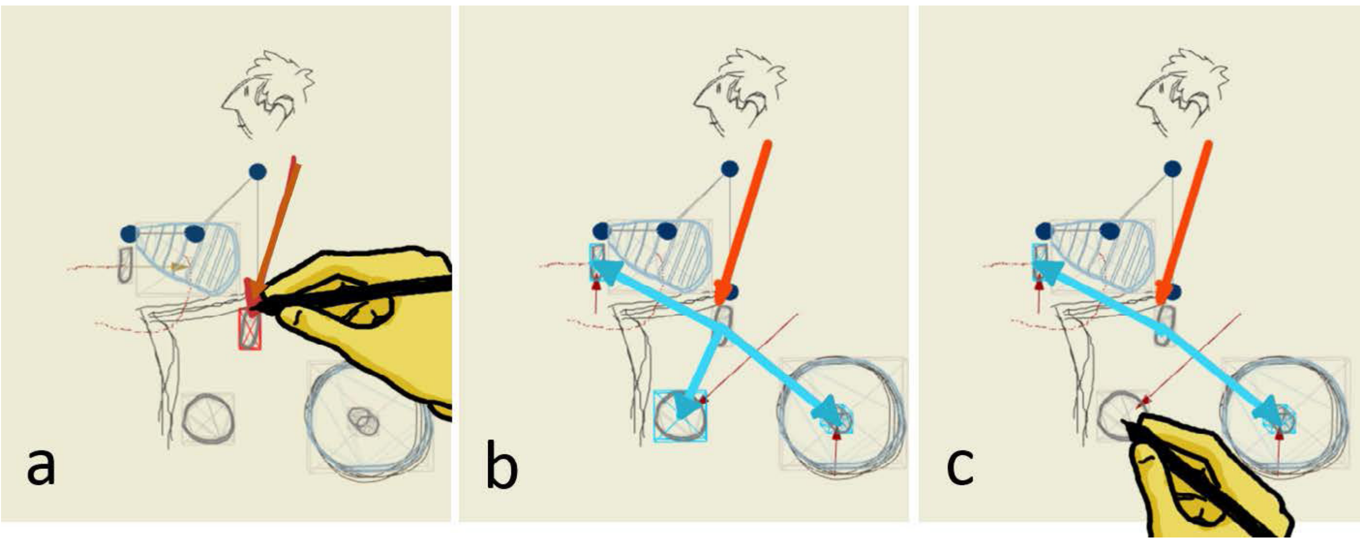

Figure 41: Illustrating how to draw a load(a) and anchors(b) in DreamSketch[4]

6.7. Conclusion

The number of available research papers regarding generative design at the time of writing is quite limited. But after a thorough analysis of the literature, six statements can be made about generative design in its current state:

1. *It is difficult to choose and implement a correct set of parameters.*
2. *Most research is focused on progression in the AEC industry.*
3. *No focus on the integration of generative design and additive manufacturing.*
4. *The elimination process of generated designs is difficult for humans.*
5. *Creating generative designs is not yet intuitive.*
6. *Focus is still on research and not yet on real-life applications.*

6.7.1. Implementation of parameters

One limiting factor during the generative design process is choosing which parameters to include. Not only choosing, but also actually entering the correct information is experienced as difficult[7, 46-48, 56]. Generative design research projects are always partly successful, but many researchers mention that parameters need to be added and adjusted for future work.

6.7.2. Focus on AEC industry

Furthermore, extensive research is mostly focused on progression in the AEC industry. Subjects like an evaluation of quality control of buildings on certain parameters[17, 46, 55], optimum and alternative layout for rooms[48, 56] as well as planning the layout of a set of buildings[47] are common. In comparison, research into generative design for the manufacturing industry does exist such as design exploration[3, 4, 52] or production using AM[6, 53], but is more scarce.

6.7.3. Exclusion of AM

The existence of AM, while acknowledged in most papers, is not a subject touched upon in many papers. For example, it is not discussed if the designs produced by the systems utilised in the research are feasible to produce with AM. Even if research considers the fact that generative designs can be made using AM, it does not consider the flaws or restrictions. A point often overlooked is the layer for layer production method, the maximum size or the possibility of porosity of FDM which can cause complications in the final product.

6.7.4. Elimination of designs

Programmes that assist designers during the elimination process is an additional concern[13, 55, 58]. It is possible to generate thousands of designs[17] but the same advantage that generative design offers, a wide variety of new designs, is a disadvantage as well. First, designers cannot analyse each design individually and compare them to all other variants. Second, the elimination process would be too time-consuming. Products or methods such as the Dream Lens[13] or the multi-agent system developed by Gerber[55] try to help the designer during the elimination process. Unfortunately, their research is not yet implemented or available for industries.

6.7.5. Create generated designs

Current CAD software limits the creativity of the designer and ease of use when exploring new designs. New applications such as the DreamSketch[4] or Genoform[57] offer new, more creative and easier techniques to produce generated designs. While Genoform is an existing product and plug-in for several CAD programmes, DreamSketch is not yet available to the public.

6.7.6. Focus on research

Unfortunately, a common theme among research in generative design is that real-life applications are on the background. Many researchers have not developed anything ready for the market[4, 7, 13, 18]. The industry's focus is rather into researching the problems than actually realising solutions[58] while improvement for generative design applications is a must. Research has proven the advantages of generative designs multiple times. Yet, it is not available for smaller companies or certain industries due to lack of affordable CAD software that supports it.

6.7.7. Summary

In conclusion, research into generative design is ongoing but the results are mostly not yet ready for an introduction to the market. It is currently not feasible to implement the current developments of generative design into software that is available and affordable for businesses.

Furthermore, it is difficult for human designers to enter the correct parameters, choose between multiple designs or release their creativity when using software that supports generative design. Lastly, even if the designer achieves a generative design, considerations need to be taken into account to manufacture it using FDM. A gap between generative design research and an actual ability for smaller companies to produce them exists and needs to be bridged.

Chapter 7

Market research

In this chapter, I will give the results of the interviews with various clients from Dddrop 3D printers. A small range of companies was selected by Dddrop 3D printers with different backgrounds and opinions about 3D printing to get a general view on the state of mind and developments in SME's regarding generative design. The support team of the Dddrop printers were also interviewed together with executives and consultants at Dassault Systèmes. I will end this chapter with a conclusion about the current mindset of SME's about generative design in combination with FDM printing.

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7.1. Interview with SME's

The interview questions, as can be seen in Appendix C, were divided into four sections. The first section contain general questions about the company itself to get a feel for the company. The second section is research into how companies use their FDM printer and their experience with it. The third section focuses on software to see why they use certain software. The final section is about generative design and is used to get an insight into the potential interest of companies. The following sections will summarise the insights gained in these sections. Appendix D contains a table with all companies and their shortened answers to the questions.

7.1.1. FDM printing

Clients of CAD2M mainly use FDM printers for five purposes:

1. *Prototyping to test and preview designs for themselves and clients.*
2. *Developing moulds for other materials.*
3. *Fabricating plastic parts for their own products.*
4. *Develop their own specialised tools for their machines.*
5. *Printing cases and holders to improve the storage in their own workspace.*

As for printing preferences, companies have different wishes for different purposes. This is logical because a simple prototype does not need to be as perfect in comparison with production products. For example, for prototypes the printing speed is more important than the accuracy of the print itself. In contrast, prints used as a product or tool require a higher level of detail which results in lower printing speed.

The consensus among clients is that they want the least amount of post-processing such as removing support material and sanding. Likewise, adjusting settings in the slicer software to optimise the printing process takes up too much time. Clients wish for a plug and play experience in which the least amount of adjustments are needed to achieve a well made product.

The material most companies prefer is PolyLactic Acid (PLA) because it is currently the easiest and cheapest material to use for 3D printing. Easy means it is less prone to warp during printing and prints at a lower temperature which means finer details and higher printing speed. Alternative material clients use is Acrylonitrile Butadiene Styrene (ABS) which falls in the same price category. It has properties such as higher ductility, more heat resistance and no deformation under sunlight or dissolution in water compared to PLA. However, it is more difficult to print due to higher printing temperature and the risk of warping is higher which clients find frustrating.

A material which combines the best of both worlds is Polyethylene Terephthalate modified with glycol (PET-G). It is slightly more expensive but prints as fast as PLA, has less chance of warpage than ABS and is in comparison the strongest and most flexible filament. A few clients of CAD2M are already using PET-G, but only when deemed necessary even if it is a highly flexible filament which can be used for different functionalities.

The main aspects of 3D printing which are important to clients of CAD2M are precision and accuracy, plug and play settings in the slicer software and minimum or zero post-processing requirements. It can be concluded that companies want to insert a CAD model, press the start button and after a while, a perfect product is the result. Most companies mention they do not want to invest time and effort to adjust settings and test various prints to see which has the best results.

7.1.2. Software

The results of this section need to be taken with a grain of salt. Most clients that utilise Dddrop printers are also a client of CAD2M. Dddrop printers resell the software Simplify3D while CAD2M resells the Solidworks software. Thus, most clients that were interviewed utilise those programmes. The main reason why clients use these software packages is that it is an industry-standard in their business, ease of use and its reliability.

A variety of clients also use add-on software or specialised software which they developed themselves due to specific wishes. For example, a cancer clinic developed its own software to convert scans of their patients into STL-files. However, most clients preferred not to use add-on software if it is not necessary to reduce the amount of software complexity and expenses.

7.1.3. Generative design

Most customers have never heard of generative design before. This was not an unexpected result seeing as generative design only became more well-known in recent years. One client had worked with a generative design programme once during a workshop and another heard of it during a webinar by Dassault Systèmes. It is clear that SME's need to be informed about the possibilities of generative design.

Most clients recognised the potential advantages of generative design. Depending on the business, the advantage generative design would offer differs. The most interesting one for clients of CAD2M was the implementation of topology optimisation. Secondly, the fact that multiple designs can be generated which comply with inserted requirements. Lastly, a few companies were interested in more creative and organic designs. The main restriction for companies was that they did not know how to use it and had never heard from it before. If there was an opportunity to gather more knowledge about generative design, companies would be more willing to use it.

Several clients mentioned that generative design would not apply to them. For instance, a police department uses 3D printing to make physical crime reconstructions. These need to be as close to reality as possible so multiple designs are kind of unnecessary. An optimum result is also inapplicable in this case. Another company uses 3D printing to make very small parts for other companies. These parts are so small and precise that adding restrictions and parameters would take up more time than it would save. Lastly, one client mentioned that generative design would be very useful to explore designs. But the client was worried that the generated designs would not communicate the brand. Their product line is carefully crafted so the products show the brand image to consumers.

7.1.4. Conclusion interviews SME's

First of all, the awareness and general knowledge about generative design among SME's needs to be raised. To move forward and innovate, SME's need to know about future upcoming technologies. The advantages of generative design need to be highlighted because it was difficult for clients to visualise it during an interview over the phone.

Secondly, it needs to be implemented in such a way that designers can immediately work with it without too much difficulty. It needs to integrate with their current work methods to reduce the amount of change in workflow. Clients mention that they did not want to use generative design if it would cost too much time to learn about it and integrate it. Several clients mention that their younger colleagues were more willing to learn generative design and have better capabilities to learn it.

Lastly, it seems that companies are not aware what topology optimisation is. This is a great first step for SME's to use this algorithm to experiment with more difficult shapes. And a great stepping stone towards implementing a generative design process.

7.2. Interviews Dddrop

The interviews with Dddrop employees were held to get a general opinion about the wishes and experiences of their clients. In general, the information gained by interviewing clients is compliant with the personal experiences of Dddrop employees. The only difference was the experience with the printing preferences of clients. Dddrop employees mentioned that printing speed is the most important aspect for clients. Whereas their clients mention that the accuracy of 3D printing is more important than the printing speed.

7.3. Discussions Dassault

The opportunity arrived to discuss generative design with two executives, namely a sales and simulation executive, and a few technological consultants at Dassault Systèmes. An attempt was made to reach out to the 'generative design experts' of Dassault, but there was no response.

Due to the uncertainty of their exact roles in the company, it was difficult to compose interview questions beforehand. The choice was made to instead write down some discussion points of which the most important one was generative design. The discussions resulted in two interesting findings.

7.3.1. Market pull vs. technology push

CAD companies have an interesting company structure which consists of three main business pillars as seen in Figure 42. The industry teams (marina offshore, architecture), the brands (Solidworks, Simulia) and the go-to-market (sales). The industry teams look at very specific industry requirements and specify to the brands what these industries need. The brands develop tools to fulfil the needs and hands the software to the go-to-market. The go-to-market then tries to convince various companies of the added value of the software for sales. This system, while efficient, lacks in innovation. The focus is on a market pull instead of a technology push.

The problem with a market pull strategy is the fact that it lacks innovation. Companies do not yet know what generative design is and thus will not ask for it and generative design as a result will not be the focus of the software company.

7.3.2. Internal communication

Dassault Systèmes is an enormous company with various regions and locations worldwide. Adhering to one congruent definition is difficult which is noticeable when looking at the various software Dassault has developed, see Chapter 8.

The names for smaller software packages in the 3Dexperience platform change constantly to attract the most customers and creates confusion within the company as well. It is clear that a link between the various departments is missing.

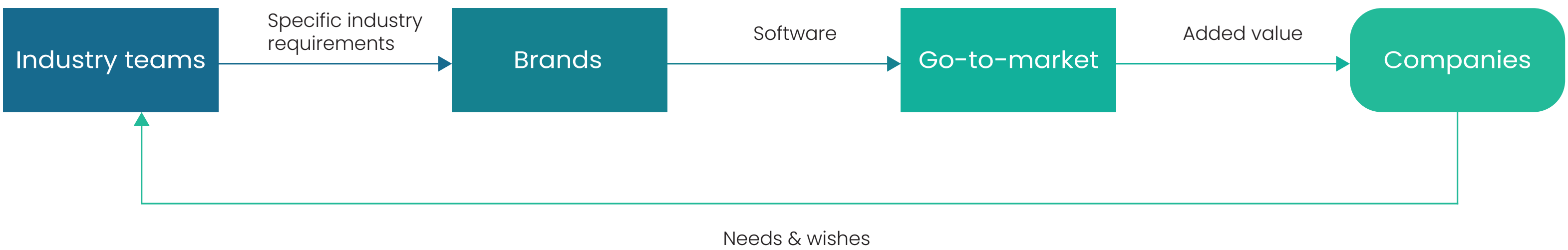

Figure 42: The business pillars of Dassault Systèmes

7.4. Conclusion

The interviews with SME's are conclusive and lead to a summation of thoughts about generative design in combination with 3D printing. A summarised list is given which will be substantiated it in the paragraphs below:

1. *Raise awareness of generative design*
2. *Plug and play*
3. *Accuracy is more important than speed*
4. *Easy transition to generative design*
5. *Generative design can mostly be used for concept and strength exploration*
6. *Companies are not compelled to innovate*
7. *Generative design definition not congruent in software companies*

Only one SME knew about the existence of generative design. It is clear that before integrating generative design into the workflow of SME's, knowledge and awareness about its existence is necessary. Specifically, the specific advantages that generative design can bring the company should be highlighted. It was difficult for interviewees to visualise the advantages and several companies were hesitant for change.

As soon as SME's are aware of generative design, the transition of the traditional CAD process to a generative design process should be smooth. Arguments why SME's would not want to learn generative design were a lack of time and energy to educate themselves and integrate it into their processes. The SME's need guidance and tutoring to incorporate generative design.

In combination with AM, generated designs should be plug and play. It was clear that SME's prefer CAD models which can immediately convert into STL files and be produced without too much interference from the user. Thus, the software should be able to generate designs which are incorporating DfAM rules. As for 3D printing itself, it is still not accurate enough so 3D printers should improve.

Many SME's use manufacturing processes which are stronger or vastly different from 3D printing. Generative design in combination with FDM printing should have its focus on design and strength exploration to discover the weaknesses and flaws of certain designs before production. Because FDM is very fast and cheap compared to other processes, it is by far the most ideal manufacturing process for prototyping.

As for CAD companies, two main findings were the current business model, which does not favour innovation, and difficulty of a widespread standard definition of industry terms. For SME's to accept and incorporate generative design, CAD companies need to improve these two factors.

Chapter 8

Software research

In this chapter, I will use various software packages from Dassault Systèmes which showed the most promise regarding a generative design aspect. Additionally, I will analyse two competitors of Dassault Systèmes using online desk research to compare their progress regarding generative design. I will end this chapter with an analysis of the current software and a conclusion if SME's can use generative design in its present state.

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8.1. Analysis process

This chapter is research into currently available commercial software. Multiple CAD tools will be tested to see if they use true generative design. As mentioned in Chapter 5, the author was limited in software packages. The following CAD software by Dassault Systèmes were tested while their direct competitors are analysed based on an online desk research:

- *Solidworks Simulation 2020*
- *xDesign*
- *Functional Generative Design*
- *xGenerative Design*
- *Siemens*
- *Autodesk*

Each software will be evaluated on certain specifications to determine if the software uses a generative design process. These specifications are based on the definition of generative design as determined in Chapter 3. The following specifications are evaluated:

1. *Inclusion of nonstructural parameters.*
2. *CAE analysis can iterate based on previous iterations of the model.*
3. *Algorithms can remove and add material to a design.*
4. *An incomplete CAD model can be used to do an analysis and generate designs.*
5. *Analysis of the CAE is accurate and trustworthy.*
6. *Programme can give multiple results in one step or very quickly.*
7. *Broad additive manufacturing controls are included.*

These specifications were chosen because they are deemed necessary for CAD software to incorporate true generative design. The only exception is the last specification which is not necessary for software to have true generative design capabilities. However, because AM makes the production of generative designs easier, this factor is included to see if the software already includes AM constraints.

Figure 43 shows the analysis process used in this chapter. Each software package will have a short introduction. Secondly, a short description of the user interface is given. The third and fourth step will look into the pre-determined specifications and next any further considerations are mentioned. The analysis will end with a conclusion and a table showing which specifications are fulfilled.

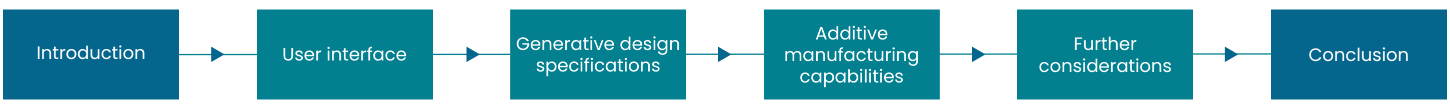

Figure 43: Analysis process of the software research method

8.2. Solidworks simulation

The first programme whose capabilities are tested is Solidworks 2020 Simulation. The professional and premium edition has a tool called 'Topology study' which will be evaluated. The premium edition of Solidworks was used during this research.

8.2.1. User interface

Solidworks Simulation has an easy user-interface as shown in Figure 44. Companies familiar with the basic Solidworks interface have a clear advantage and will quickly understand how it works. On the left is the feature manager design tree which contains all bodies, sketches and other parts of the design. The standard toolbar is used to save, load or adjust settings. The command manager is context-sensitive and provides actions and commands corresponding to the tab chosen by the user. The middle section is the graphics area which is the main screen where models can be controlled.

8.2.2. Generative design specifications

An advantage of Solidworks Simulation is the extensive options available for CAE. The user can integrate very accurate details in the model regarding the load case. After running a simulation, the user can see graphs and heatmaps of the final iteration so the user can properly analyse the result.

Unfortunately, the parameters available are all structural and the user is unable to implement nonstructural parameters. Another disadvantage is that the programme can only remove material which is already available in the CAD model.

As the name implies, this programme is an extensive topology optimisation tool and optimises a previously made CAD model instead of generating its own geometry. The result is only one model.

8.2.3. AM capabilities

The topology study does not take into account DfAM. The resulting STL-file needs a lot of support material in internal holes which is very difficult to remove. Even when a user removes most support material in the slicer software, the result is not optimum as shown in Figure 45 and 46.

The thin connections, even with a minimum thickness setting of 5mm, are not very strong. The bridging between material is also sagging without support material. In conclusion, support material is very much a necessity and a lot of undesired post-processing is required.

The topology study does include a few manufacturing controls such as minimum thickness and preserved faces. It resolves a few AM problems such as too small thicknesses. But, it is insufficient to resolve all problems which means that users need to correct a lot of details.

8.2.4. Further considerations

The topology study is a very handy tool and is intricate enough that users can define a good load case scenario. Especially analysing results is very easy with automated graphs and displays which can be edited in the application. Users are advised to carefully analyse the results because the programme sometimes uses confusing colours to display results. These colours might lead users to believe a part is strong in a certain area, while in reality, it is the opposite.

Moreover, many companies are familiar with Solidworks software packages. This makes the step from Solidworks Basic to Solidworks Simulation an easy one.

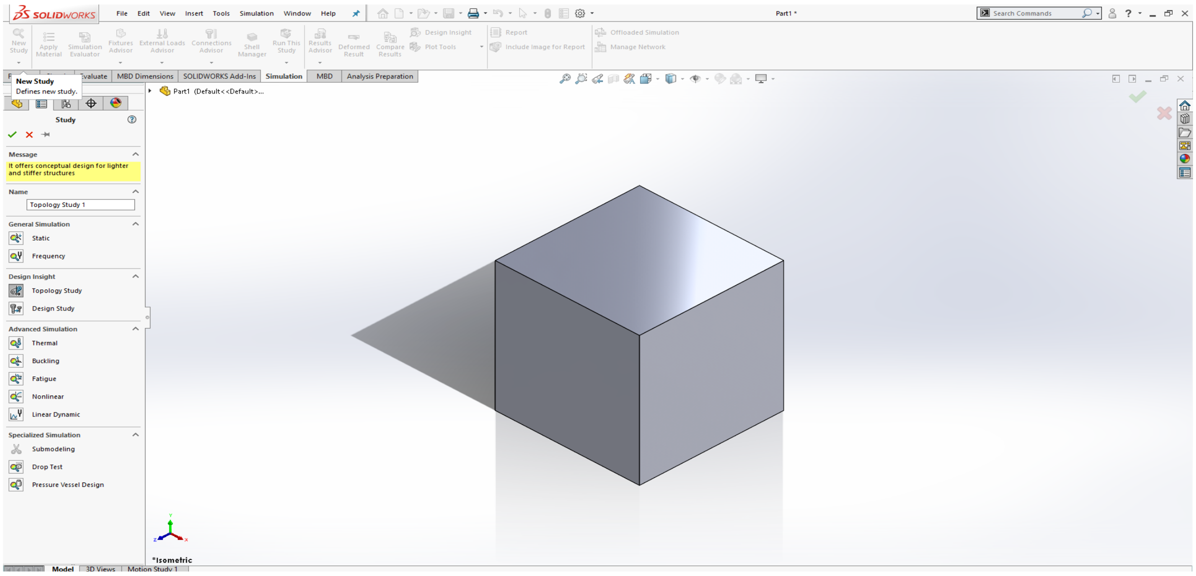

Figure 44: User interface of Solidworks Simulation

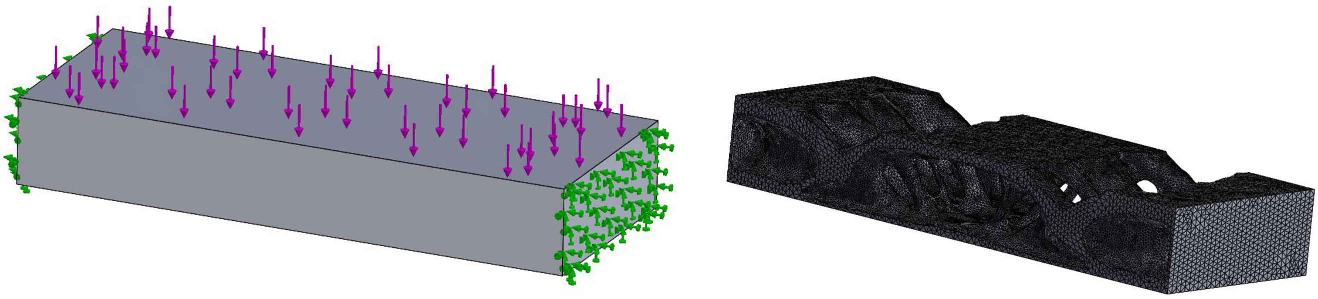

Figure 45: A basic model with clamps on the side and a force from above of 200N. The left picture is the initial model and the right picture is the topology optimisation result.

Figure 46: Two prints of the model above. They are the same but the first prints has been stopped midway the process

8.2.5. Conclusion

The specifications to incorporate a generative design process are lacking as seen in Table 4. The topology study can only provide one optimum design which, depending on the size and complexity of the parameters, can take a long time to simulate. For instance, the simple design in Figure 45 took about thirty minutes to simulate. This makes it impossible for the simulation to provide multiple designs in a short period.

Furthermore, the software can only remove material from a fully developed model. If the model is incomplete, the mesh may succeed but the simulation results are inaccurate or just result in a failure of the simulation.

8.2.6. Design study

A quick look was taken at the 'Design study' tool which is also an option in the Solidworks Simulation package. This study allows users to assign a range for certain parameters, such as thickness or length, in which Solidworks can vary. For example, the height of the product may vary between 10 and 15 millimetres. Solidworks combines different variations of the indicated parameters and runs quick FEM simulations while using previous FEM results. The designer or engineer receive simulations of one part in various configurations within a short amount of time(depending on the size of the parts).

However, the design study does not add, edit or remove material. It follows the guidance of the user who defines which parameters can change. Furthermore, while it generates various designs, they are all very similar and limited in its appearance. The programme does highlight the designs which have the best results which is a very useful feature. But, it is a far cry from true generative design.

	Nonstructural parameters	Iterative algorithms	Remove and add material	Incomplete CAD model	Accurate CAE analysis	Multiple results	AM controls
Solidworks Simulation		✓			✓		✓

Table 4: The generative design specifications for Solidworks Simulation

8.3. xDesign

An application that is integrated into the Dassault Systèmes cloud platform 3DEXPERIENCE is xDesign. It is the more innovative little brother of Solidworks which works in your browser, no installation necessary and all your designs are immediately synced and made available to your colleagues. It is still early in its development and has some quirks which makes CAD a little bit more difficult. The pros of xDesign are that it is already integrating new and more innovative methods of modeling in its software. For example, topology optimisation and a simplified form of generative design are already implemented.

8.3.1. User interface

xDesign has a familiar user interface for people familiar with Solidworks software as shown in Figure 47. On the left is the design manager tree which contains all sketches, features and other components of the model. At the bottom is the toolbar with a variety of tabs that group similar tools together. The blue bar at the top is the general 3DExperience toolbar which every application in the platform uses. Lastly, the middle section of the programme is the graphics area in which sketches and features can be created and shown visually.

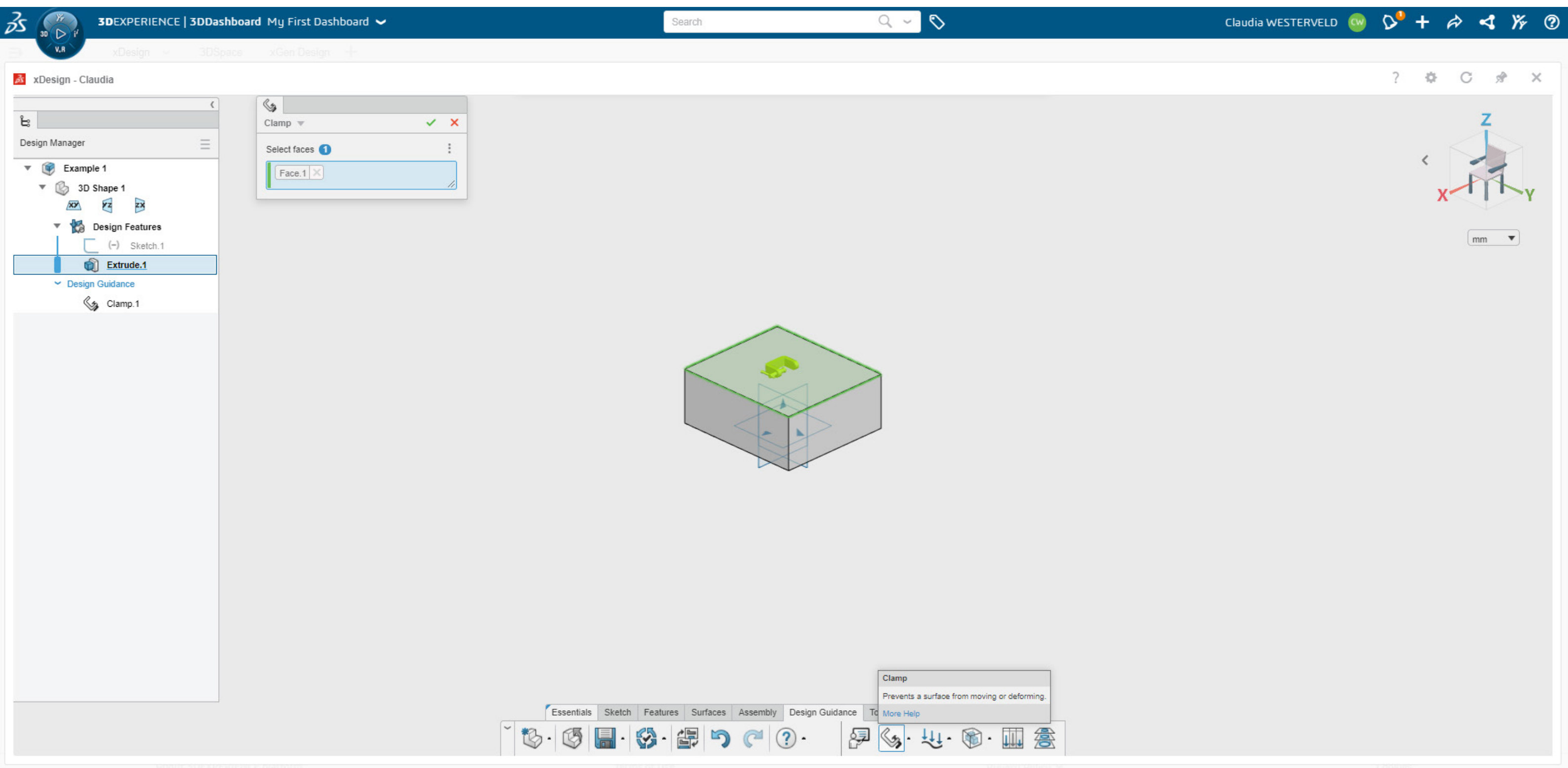

Figure 47: The user interface of xDesign

8.3.2. Generative design specifications

xDesign has a tool called 'Design guidance' as shown in Figure 48 which can create new geometry using sketches, bodies and loads as boundaries. Furthermore, it can also redesign full CAD models which is called 'redesign', a rudimentary form of topology optimisation.

The generative design feature of xDesign has a couple of flaws. It only works with very rudimentary structural parameters. These parameters are limited to simple forces, clamps, design space and user-defined sketches, faces and bodies.

The algorithms which are used are iterative, you can see the design change shape and form per iteration during the calculation process. The new design is shown in blue as can be seen in Figure 49. Material in the design space during the calculation is not only removed, but also added during the process without the need for a fully defined CAD model. A disadvantage of the algorithms used is that there is no summary or indication for the user why the programme made certain design decisions. There is no CAE interface and the programme does not show proof if the model can carry the load given.

Lastly, a generated design can be easily adjusted to achieve a desired mass using a slider as can be seen in Figure 48. Unfortunately, the programme does not provide any other designs. It finds an optimum, similar to topology optimisation, without the need for a fully-defined CAD model.

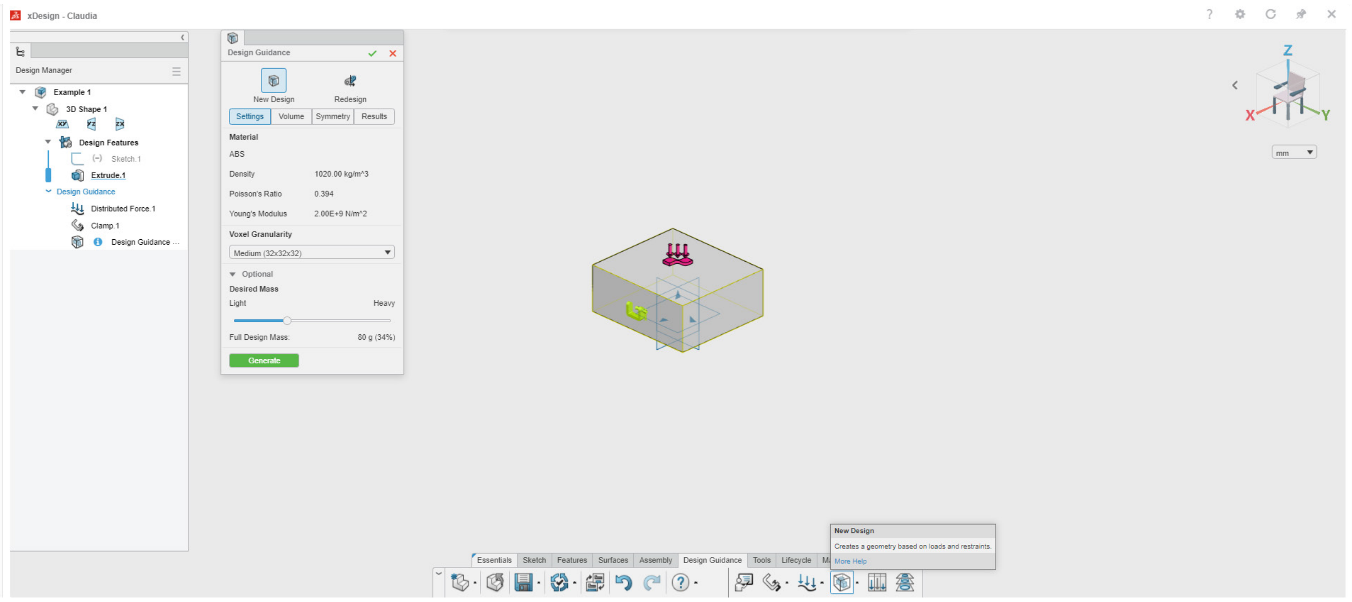

Figure 48: Design guidance tool with a load(purple) and a clamp(green)

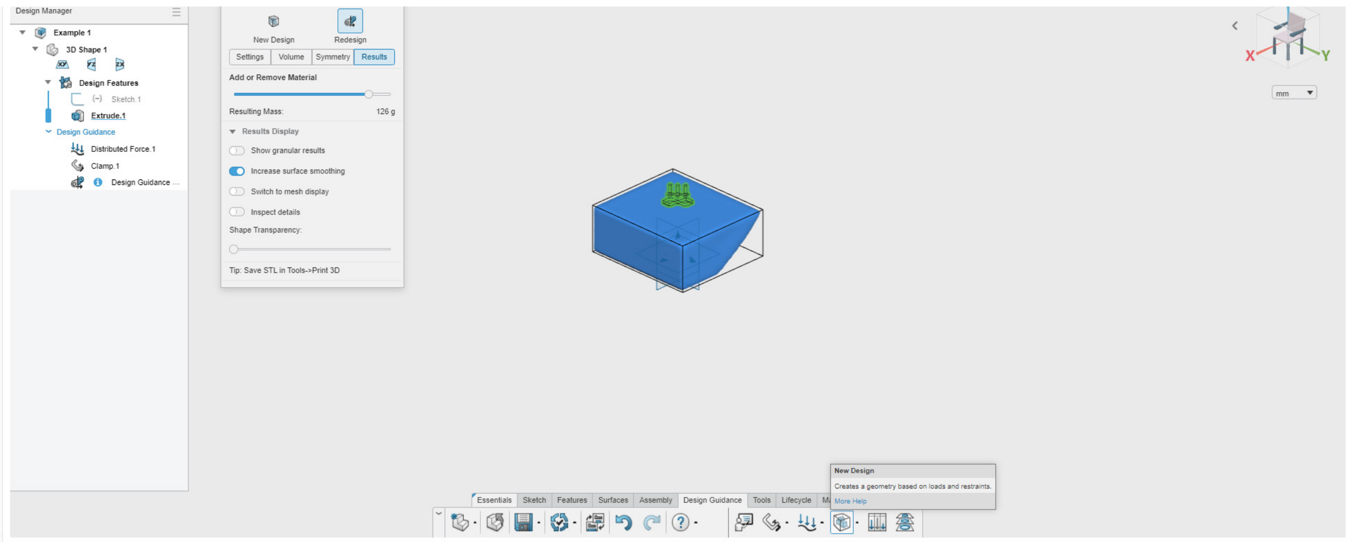

Figure 49: Design suggestion in blue and the mass slider

8.3.3. AM capabilities

xDesign includes its own 'Print 3D' interface as shown in Figure 50. The user can choose which plane will be the base of the print and which envelope the 3D printer has. The model is projected onto the base plate in which users can show the print layers and areas where support material is necessary.

Figure 51 shows the first tests of 3D printing designs made with xDesign. The programme was tasked to make a connection between two profiles and withstand pressure from the hard push of a hand(200N). Both objects have the same upper circular profile with a different bottom profile. Additionally, the object on the right was allowed more material to distribute.

These simple connections between two profiles was easy and pretty fast to produce. But an increase of complexity already results in faults as show in Figure 52 which contains floating material. The programme does not consider any design rules for AM while it does have a specific function to convert designs to STL. Overhangs larger than 45° are common and most designs not to utilise the advantages of AM. For example, the objects in Figure 51 could probably utilise less material to achieve the same strength going off designer's intuition.

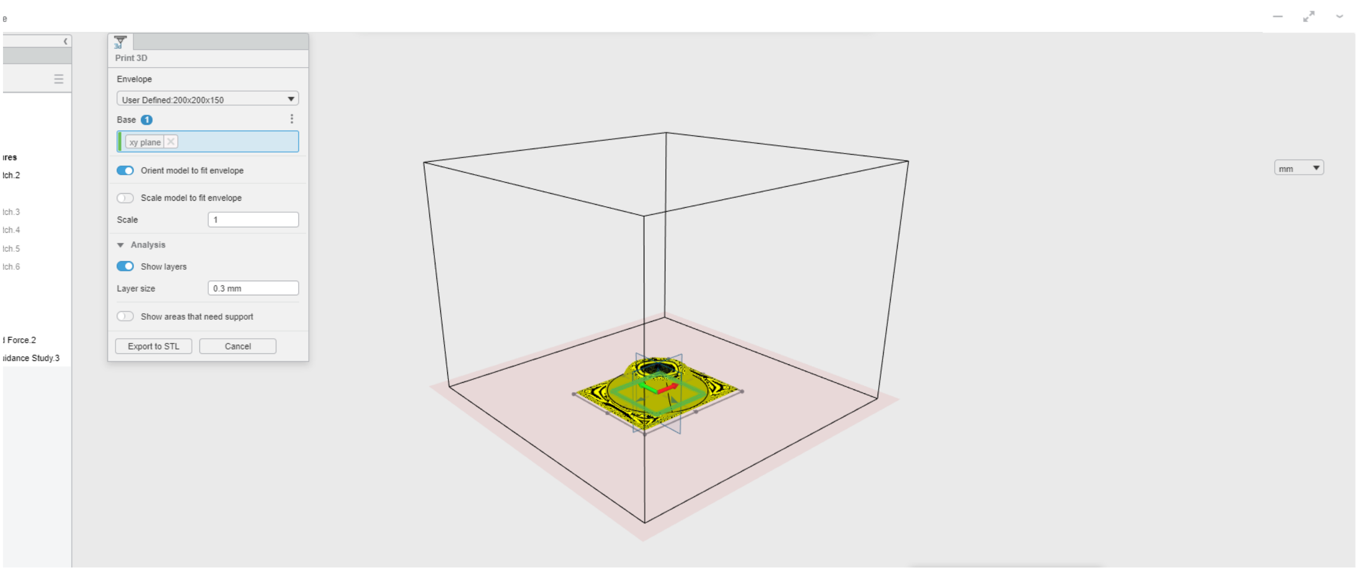

Figure 50: Interface of the 'Print 3D' tool

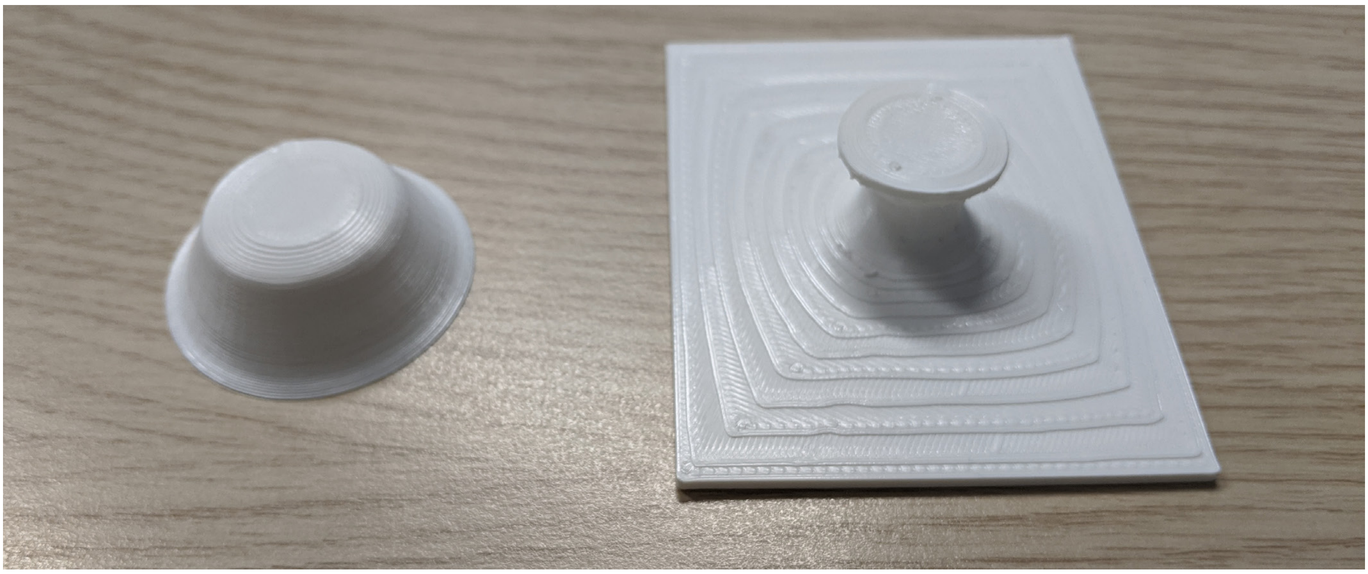

Figure 51: Two 3D print tests using simple profiles

8.3.4. Further considerations

The biggest disadvantage of the 'Design guidance' tool is that it only creates a shape and no solid body. The designer has to insert profiles, as shown in Figure 53, before using features such as a loft to transform the shape into a solid body. This is a tedious and time-consuming task that does not work if the shape is too complicated with tiny holes or sharp corners.

Furthermore, the programme has a fixed limit of a maximum of eight profiles which may not be detailed enough for larger objects. Even simple designs such as the one in Figure 53 already show discrepancies between the generated design and the final CAD model.

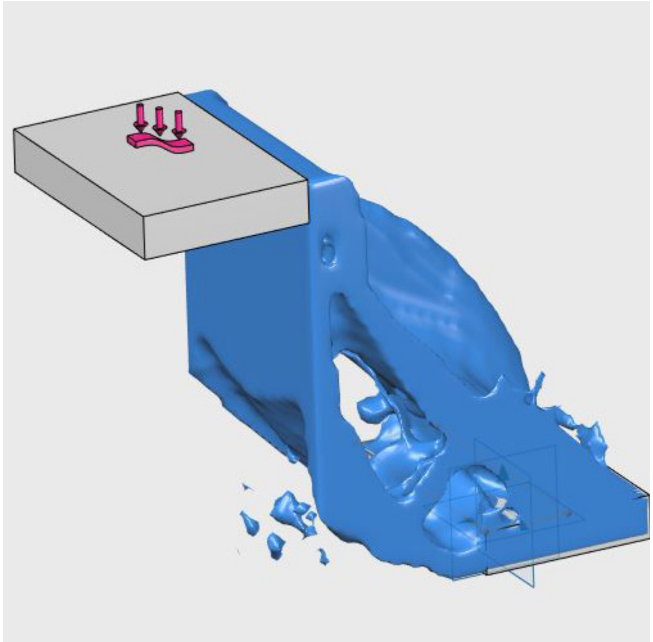

Figure 52: An attempt to connect two cubes using xDesign

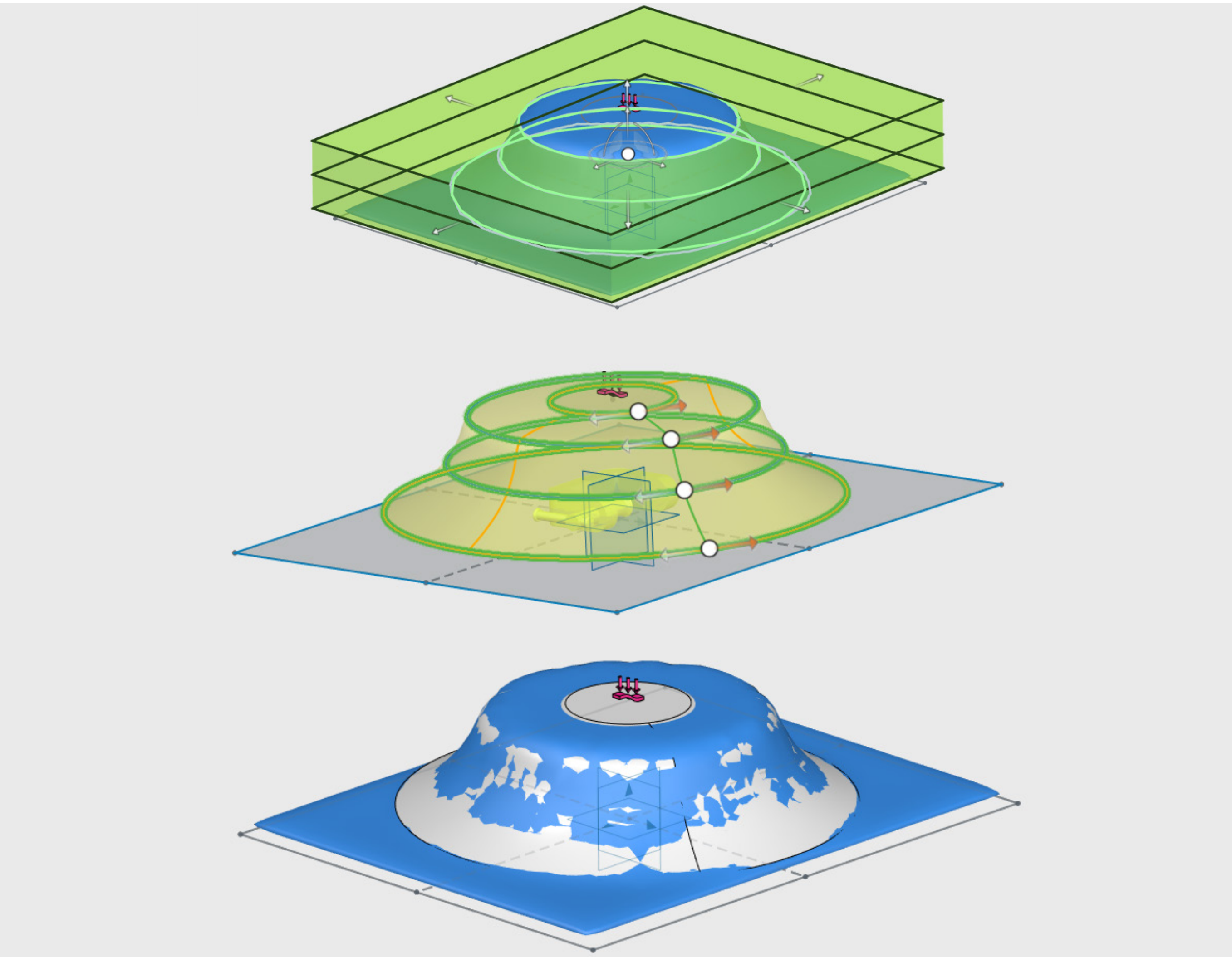

Figure 53: From creating profiles, to lofting, to a design(grey) compared to the generated design(blue)

8.3.5. Conclusion

In summary, xDesign is a programme that lacks certain specifications to achieve a true generative design process as shown in Table 5. It is one of the few programmes which has algorithms that add material to a CAD model with limited geometry. However, The CAE is rudimentary at best and cannot be checked by an engineer which makes the validity of the simulation questionable.

The input allowed in the programme is very limited and the state and validity of the simulation is impossible to control. Furthermore, the result is only one suggestion. As the name 'Design guidance' already indicates, it is a tool that should only be used to get inspiration. xDesign is still in an experimental phase in the opinion of the author and while it might produce generative designs in the future, in its current state it is insufficient.

	Nonstructural parameters	Iterative algorithms	Remove and add material	Incomplete CAD model	Accurate CAE analysis	Multiple results	AM controls
xDesign		✓	✓	✓			

Table 5: The generative design specifications for xDesign

8.4. Functional generative design

The application functional generative design is based on the high-end CAD/CAE Catia software package. This application is incorporated into the 3DExperience platform to offer cloud-based advanced software to corporations. Designers can upload or create models which can be directly analysed and calculated in the cloud.

This piece of software is, Dassault Systèmes was dodgy about an exact price indication, pretty expensive compared to Solidworks. It has to offer big advantages before SME's consider this piece of software. Another question is if they can even afford it.

8.4.1. User interface

The user interface of functional generative design is similar in comparison with xDesign. The application only differs in the tabs and tools the application has.

Functional generative design also offers tools which take the user step-by-step through the process as shown in Figure 54. It indicates to the user which steps need to be taken first before continuing the process. The success rate of the tool is greatly increased, because the user gets a warning between each step if the programme notices an error.

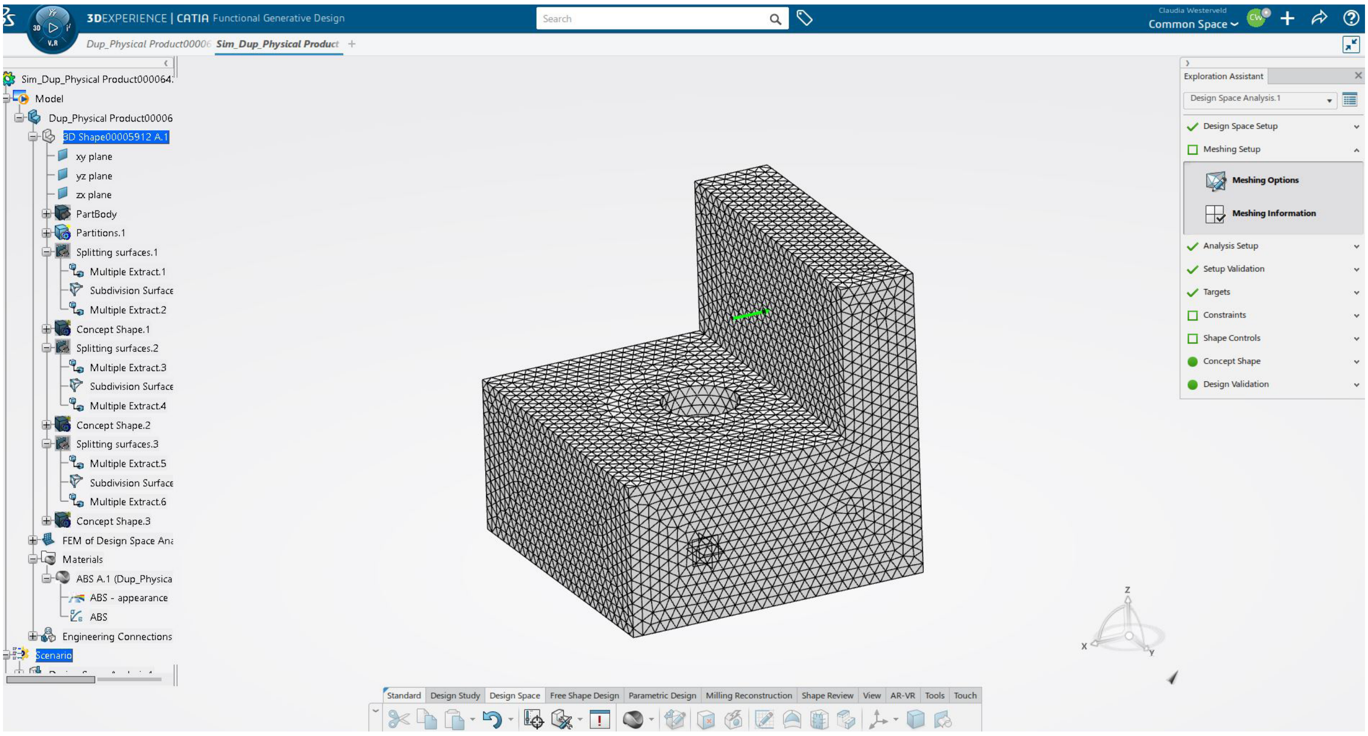

Figure 54: User interface and the step-by-step process on the right side

8.4.2. Generative design requirements

This application shows the most promise in regards towards including a generative design process. Users can incorporate, albeit it basic, nonstructural parameters such as manufacturing constraints. Unfortunately, the models needs to be complete in order to make exact and correct calculations because it does not consider that material might be added in between the model.

The CAE is very extensive and allows for fine control by the user. The step-by-step interface makes it very easy and the results are clear and extensive. The CAE has the ability to give multiple results but these are limited to the mass variations in between iterations of the calculation, see Figure 55. The variations are only slimmer and thinner versions of the initial CAD model. The algorithms are unable to add material within the design space.

The user has the option to compare various results but this is costly in time. The user has to adjust the constraints during each variant which need to be recalculated. A variation of the model in Figure 54 took about 45 minutes in addition to multiple failures during FEM calculations.

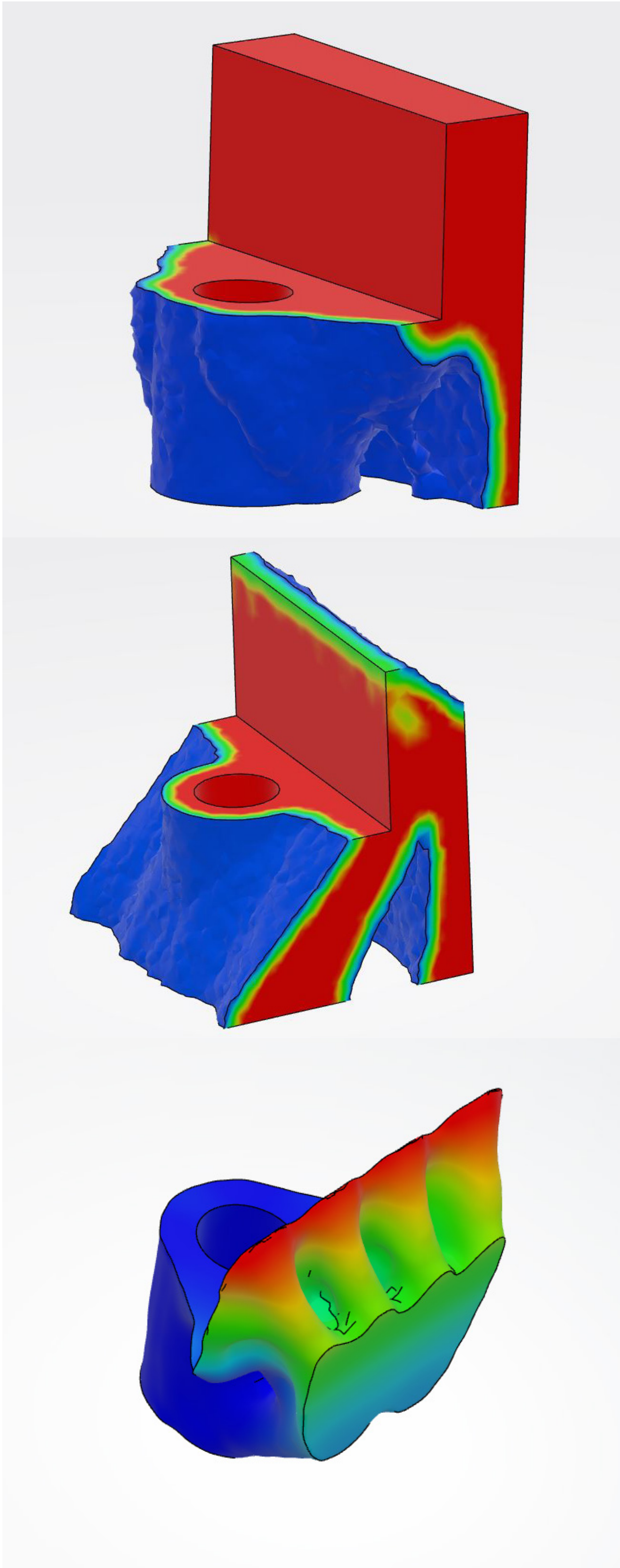

Figure 55: Different mass variations of a model. The upper model has an additional fixed face at the top.

8.4.3. AM capabilities

Functional generative design is the only software which incorporates real AM constraints. For example, you can apply a maximum overhang angle so the generated design is still suitable for AM, as seen in Figure 55. But the AM constraints were not very reliable as shown in Figure 56 where support material was still necessary.

Unfortunately, applying a maximum overhang angle is currently the only DfaM constraint incorporated. The application does allow for functional regions and a minimum thickness, same as Solidworks, but those are not real DfaM constraints.

Dassault Systèmes has an application called Delmia which offers very intricate AM controls which can be combined with Functional generative design. Unfortunately, this is also a very expensive piece of software of which the price is difficult for SME's to justify.

8.4.4. Further considerations

The CAE calculations can be run in the cloud but users need to incorporate a lot of time for the simulations to run. The simulations needs constant supervision because errors can occur halfway during the process. Additionally, if users want to compare variations of different results, they need to be present when simulations are finished to enter new parameters and restart the simulation.

It is more advanced software regarding CAE than xDesign because you have finer control and more overview. For example, functional generative design actually shows the mesh and the FEM results as shown in Figure 54 and 55. Additionally, Functional generative design is supposedly based on the high-end CAE software of Dassault. The results should be more accurate compared to Solidworks Simulation but there is no verification if this is true.

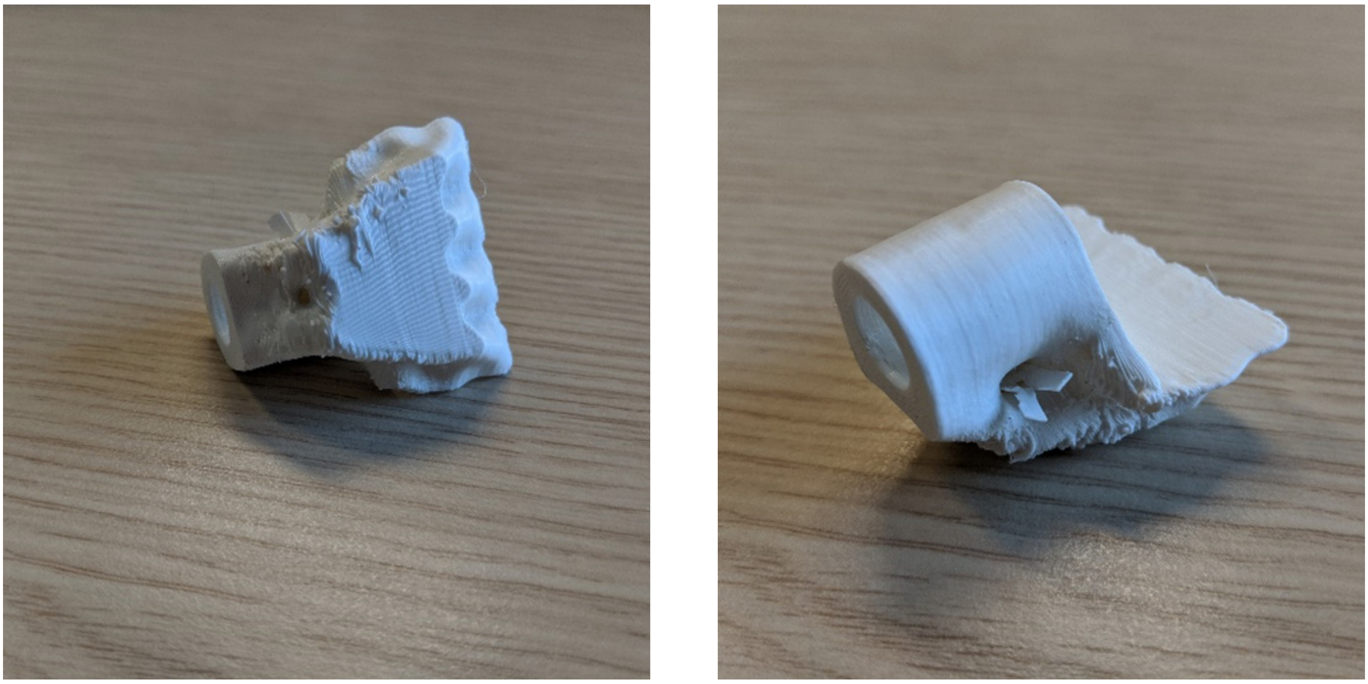

Figure 56: FDM result of previous figure in which support material is stuck in the part

8.4.5. Conclusion

Functional generative design shows a lot of promise in regards to generative design and AM. Its algorithms are extensive and the ability to save variations of results and compare them is a small step in the right direction. But it still cannot generate multiple results without intervention by the user. It still lacks intelligence before it can incorporate a generative design process, see Table 6.

The ability to add material in the design space is crucial before software can generate new variations. The application currently takes a design from the user and alters the current existing material of the model and only removes material. Also, a complete defined CAD model is necessary because trying FEM simulation with an incomplete model results in failure.

	Nonstructural parameters	Iterative algorithms	Remove and add material	Incomplete CAD model	Accurate CAE analysis	Multiple results	AM controls
Functional generative design	✓	✓			✓		✓

Table 6: The generative design specifications for Functional generative design

8.5. xGenerative design

The last application tested which is available in the 3Dexperience platform is xGenerative design. It is a very interesting application that focuses on the AEC industry. It helps users to quickly generate multiple designs by allowing the CAD model to change immediately when adjusting parameters with one mouse click.

8.5.1. User interface

At first glance, the user interface looks similar to xDesign as shown in Figure 57. The design manager tree on the left is a bit different, but other features look and feel the same. Compared to xDesign, the user interface is more intuitive in the sense that extrusions, angles and rotations can be done inside the graphics area by dragging and sliding as shown in Figure 58.

Its best feature is the introduction of the 'display graph'. A graph that displays the development of the CAD model in nodes as shown in Figure 59. Everything that the user modifies or adds in the display graphs get changed in the CAD model as well. This makes it easier for the user to adjust parameters or add modifiers. Appendix B shows multiple designs which were created within one second by randomising values. The display graph can be used on its own to create models without doing anything in the graphics area and vice versa.

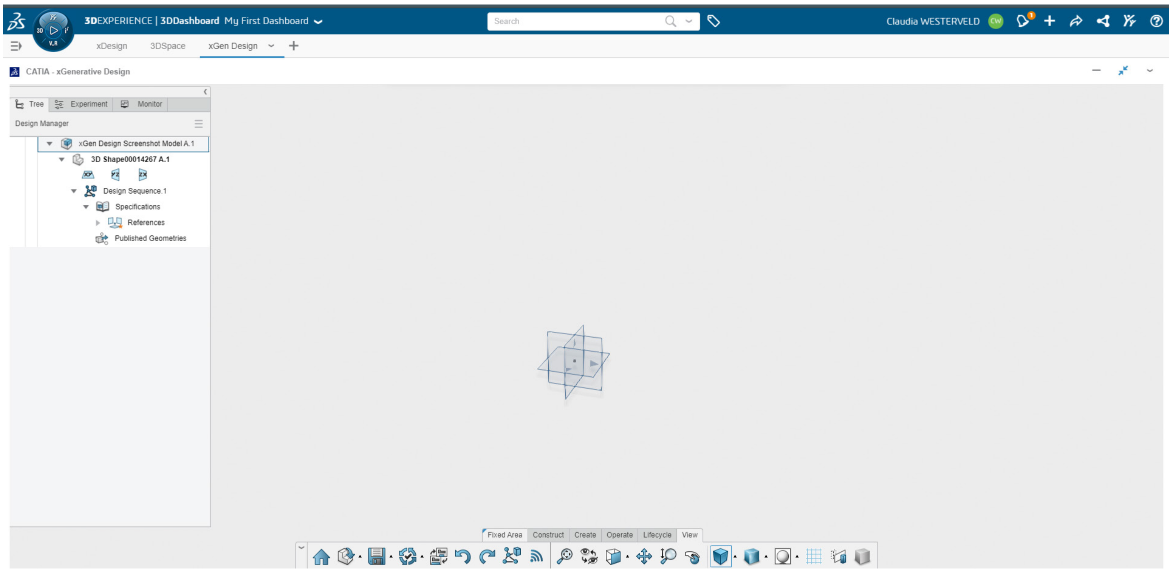

Figure 57: The basic interface of xGenerative design

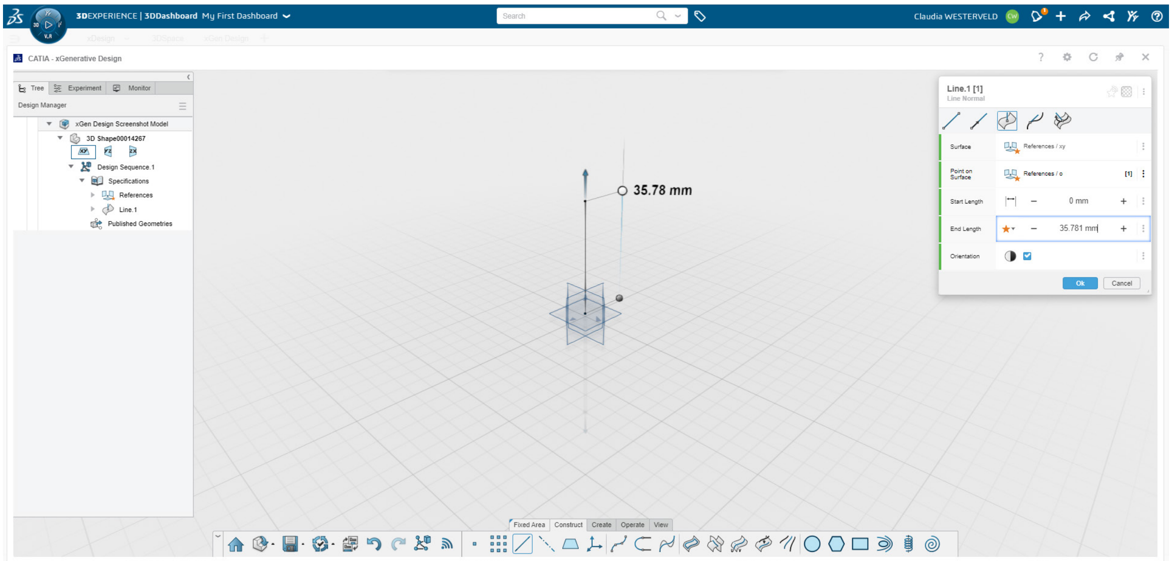

Figure 58: Dragging the length of a line

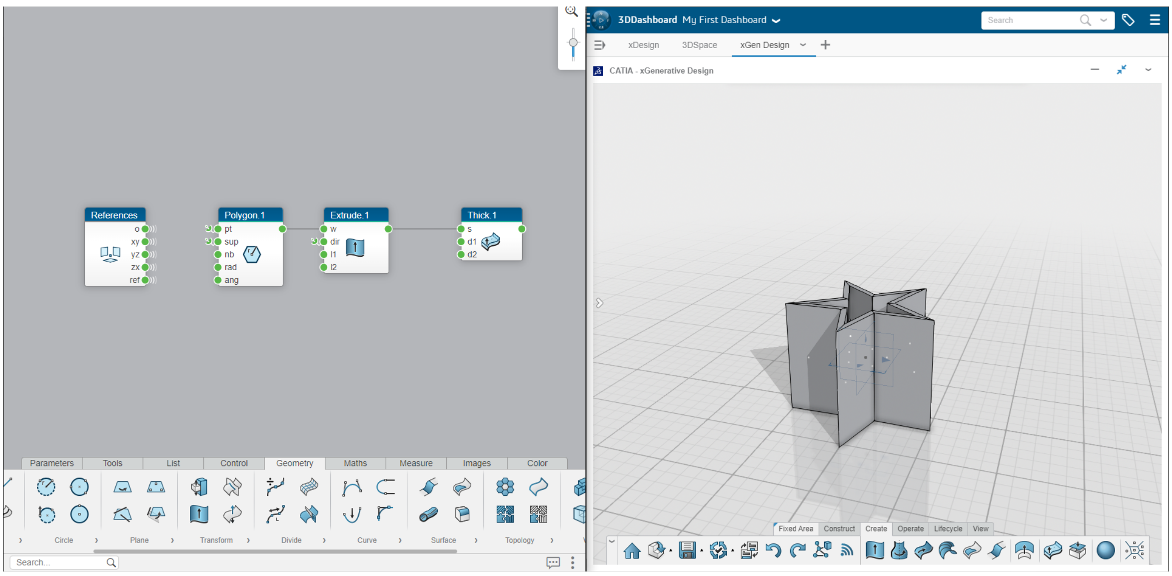

Figure 59: The same information displayed in the display graph and the graphics area

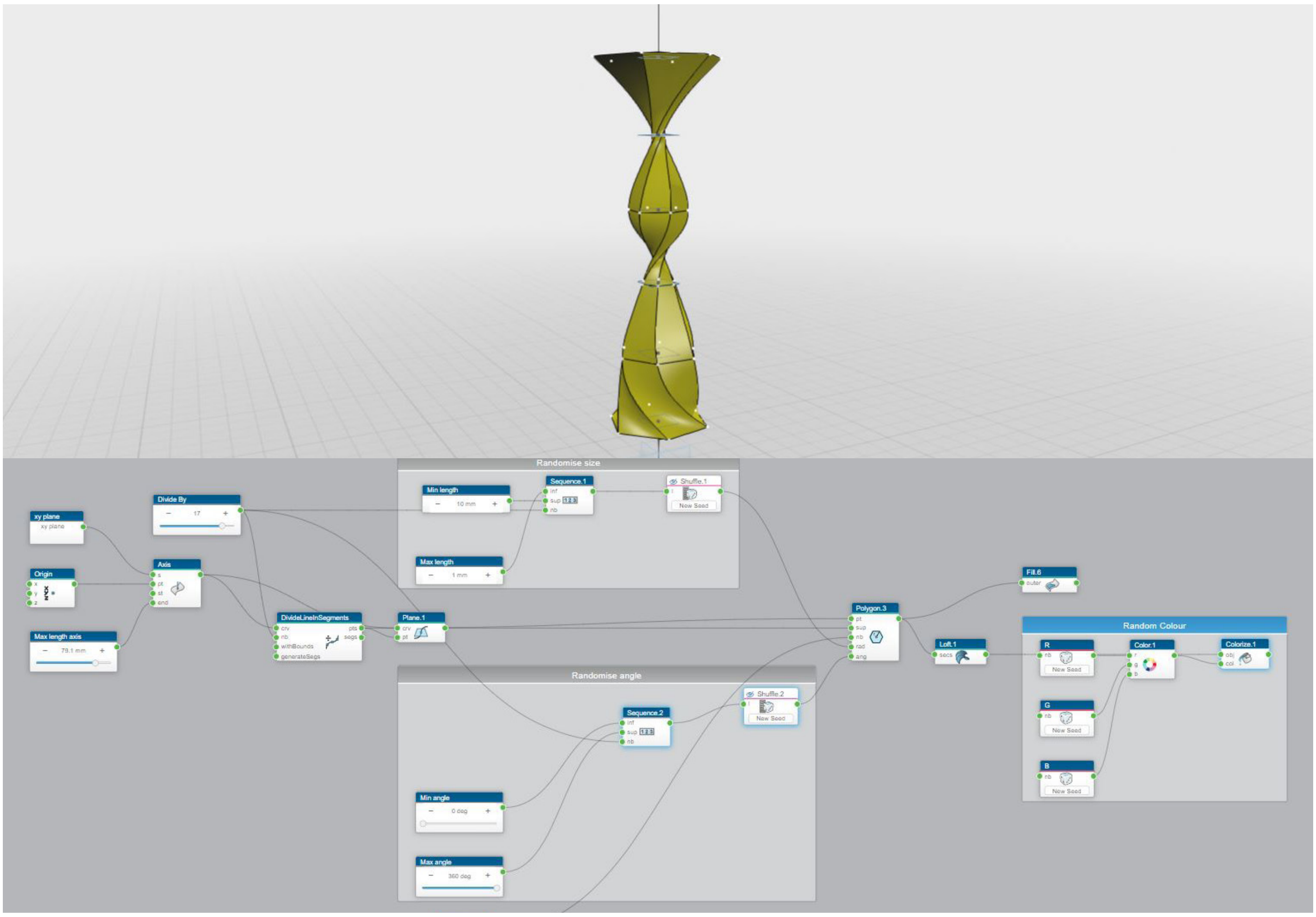

Figure 60: Randomised design in xGenerative design using the random variable

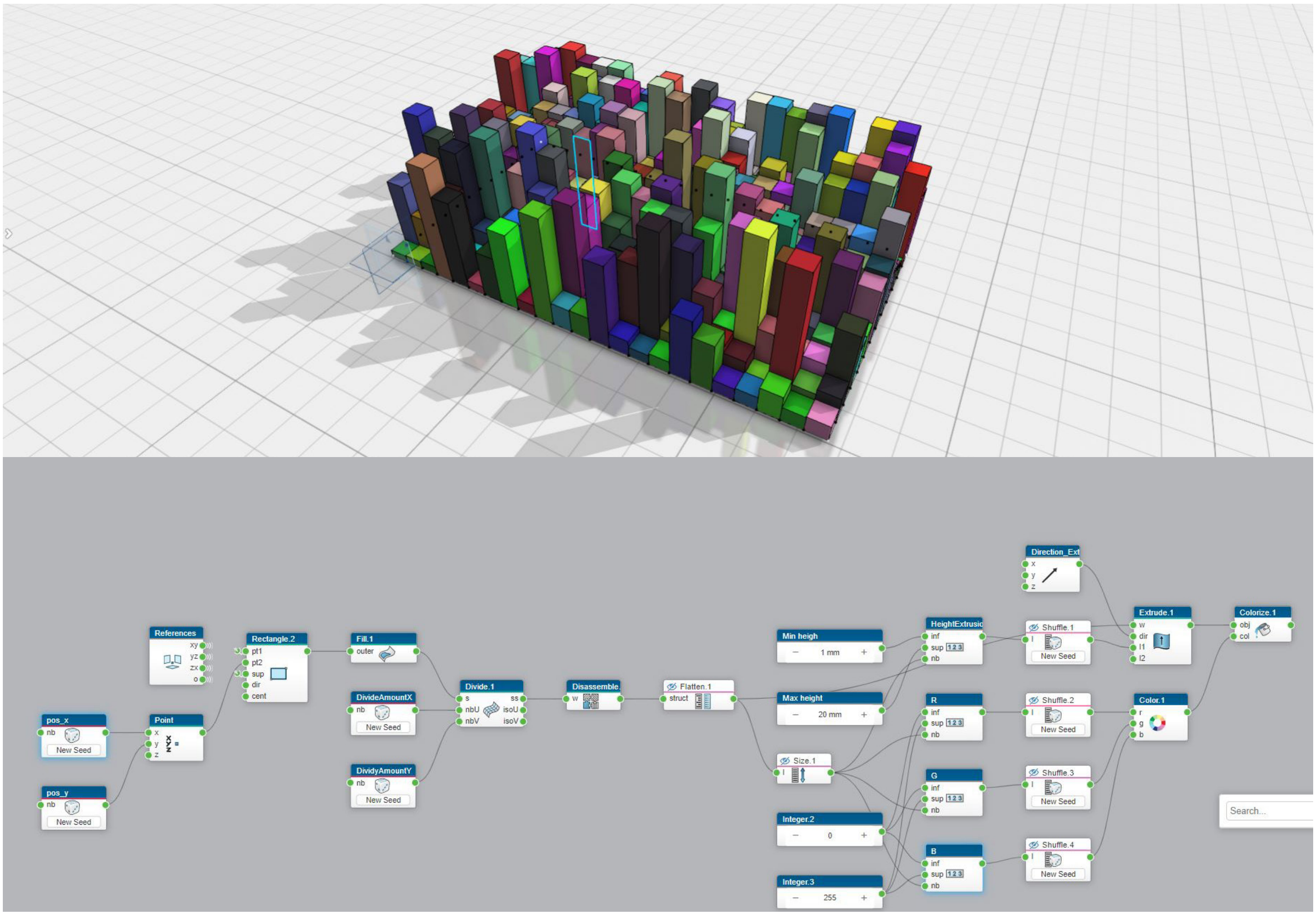

Figure 61: Another example of a randomised design in xGenerative design

8.5.2. Generative design specifications

xGenerative design is a great tool for design exploration but its missing intelligence. Everything that this programme generates is defined by the user and there is no AI (artificial intelligence) which tweaks the design by itself. The programme gives the illusion of AI because the programme can be used to get multiple results quickly. However, this is only because the programme supplies a random generator which adjusts parameters of previous nodes, also indicated by the user as shown in Figure 60 and 61.

All parameters included in the programme are geometrical with the exception of Boolean operators, mathematical operators and colours. The user cannot define parameters such as forces or maximum amount of material. Furthermore, the supplied parameters given by the user should be fully defined without any errors before the programme can compute the design.

xGenerative design does not include any CAE thus an engineer cannot analyse designs to check for displacements or stresses. The results need to be imported into other programmes of 3Dexperience to perform analyses which is inconvenient.

8.5.3. AM capabilities

xGenerative design has no option to indicate the manufacturing method. As seen in Figure 62, a design was generated which does not take into account DfAM thus it broke in the middle because the connection was too small. The programme does contain mathematical operators such as trigonometry or angle vectors which could implement design rules. For example, the user could limit angles to 45° to limit overhang. However, this would be a lot of work next to being limited in its ability to include all DfAM rules.

8.5.4. Further considerations

xGenerative Design does not allow the user to export the CAD file to the computer. The application is integrated in the 3DExperience platform which means the file can be imported to other applications. But in order to export the CAD design to an STL-file for AM, the designer or engineer has to export the file into xDesign which can convert it into an STL. This is an unnecessary extra step and costs because designers need to have a license of xDesign, or similar 3DExperience application, as well as xGenerative Design.

Another roadblock is the learning curve of the programme. While the display graph with nodes is an innovative function, it takes a while to master. The abundance of parameters and operators which can be added is an advantage, but there is no documentation yet to explain the programme and its functions.

Figure 62: A design snapped in two during removal from the printer

8.5.5. Conclusion

xGenerative design is a fun, new and innovative tool which allows designers and engineers to generate intricate and complicated geometric forms. However, its name is an injustice to its definition. It is clear that the name was used because generative design is a hot topic, but the programme has nothing to do with true generative design.

Only two of the specifications needed to call it a generative design programme were ticked off, see Table 7. However, those were generously appointed. The addition of material was within limitation of an indicated design space by the user and was more a variation of a size parameter.. Furthermore, while the programme can quickly generate a hundred designs in a couple of minutes, it is limited to the clicking speed of the user and the parameters chosen to randomise. Appendix B shows the similarity of the new designs.

In conclusion, xGenerative design shows promise but its more in the area of design generation of geometric patterns than generative design for products.

	Nonstructural parameters	Iterative algorithms	Remove and add material	Incomplete CAD model	Accurate CAE analysis	Multiple results	AM controls
xGenerative design			✓			✓	

Table 7: The generative design specifications for xGenerative design

8.6. Competitors

As mentioned in Chapter 5, to restrict the scope and because of limited demo time and financial restrictions, the software packages tested were limited to Dassault Systèmes. An online desk research was done to discover the generative design capabilities of the two other big competitors of Dassault Systèmes, namely Siemens and Autodesk.

8.6.1. Siemens

CAD software companies are very secretive of the exact capabilities of their programmes. For example, Siemens provides only one paragraph of information about the generative design capabilities of their software package Siemens NX. In order to acquire further information, sales representatives need to be contacted.

Online desk research results in various insights which indicate the current status of generative design at Siemens NX. First of all, Figure 63 shows an image of a generative design of a bracket. The worrisome part is that Siemens NX claims to incorporate a generative design process. But this image is only one of the few illustrations users can find online. It seems strange that if a true and intuitive generative design process is incorporated in the software, more images would be available.

Videos and its corresponding descriptions mostly seem to indicate that its only using topology optimisation[60-62]. The videos of the past three years also consistently use the same example to show its generative design capabilities which is suspicious. But Siemens NX has a trick up its sleeve called convergent modeling.

Most CAD software separates facet data, the mesh which is used for CAE, and the boundary representation(b-rep) data, the solid body which is used in CAD[62-64] as shown in Figure 64. Siemens NX is able to 'converge' these separate sets of data into a single model. This gives the user the ability to edit a model after optimisation, speed up the design process and makes reverse engineering easier in general[62]. The user is able to edit a topology optimisation to generate their own variations on an already optimised model.

In conclusion, Siemens NX has an integrated topology optimisation tool but with the capability to easily adjust the results with convergent modeling. While this is a significant tool which makes adjusting optimised models easier, it is no true generative design. The programme still needs a fully defined CAD model and cannot generate multiple models by itself.

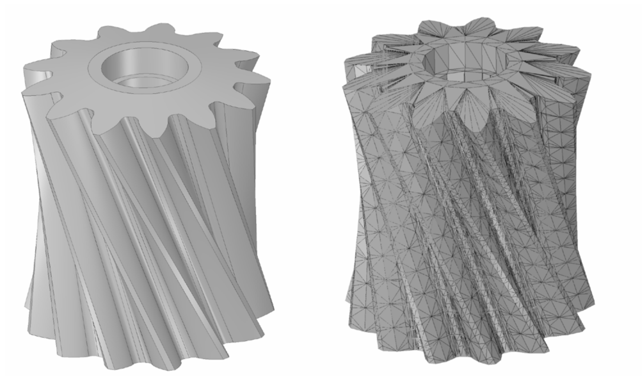

Figure 64: B-reps(left) and the resulting facets(right)[64]

Figure 63: Generative design in Siemens NX[59]

8.6.2. Autodesk

Autodesk is, in comparison to similar companies, most open about showing their plans for the near future. Autodesk has its own research projects they are working on which publishes its own papers. One of these projects is called project Dreamcatcher, a project about generative design.

Autodesk is the only company that has a definition of generative design which is congruent with that of other researchers and this thesis[65]. Autodesk understands it is no easy feat and it is probably why Dreamcatcher was initialised. Unfortunately, the current state of the project is unknown and its last publication was in 2017[4].

Similar to Siemens NX, the same images are floating around in the web which are re-used to show the generative design capabilities of Fusion 360, see Figure 65. This gives little hope for true integration of a generative design process in the near future.

Videos indicate that some of its generative design research has been integrated in their Fusion 360 software[67, 68]. It is the most progressive commercial software regarding generative design. Users can insert a CAD model and indicate how many different designs they want. These designs vary, although they look pretty similar as shown in Figure 66 and an analysis of its strengths and stresses are included. Graphs can show comparisons of results which makes it easier for designers to choose the optimal design.

Downsides are that most results are not valid and it takes a long time to get multiple results due to the speed of Autodesk servers. Furthermore, users have to pay separately for each generation next to regular software costs, probably due to server usage. This seems unfair because there is no guarantee that any results will be valid to use. It is also unclear how intricate the CAD models can be, because most videos use fairly small and simple models provided by Autodesk.

In conclusion, it seems Autodesk has the only professional software which already includes a simplified form of generative design. It does not work optimally, but can provide ideas and suggestions for concept design. Unfortunately, it is unclear what their idea is for the future of generative design.

Figure 65: A generated design of a bracket in Fusion 360[66]

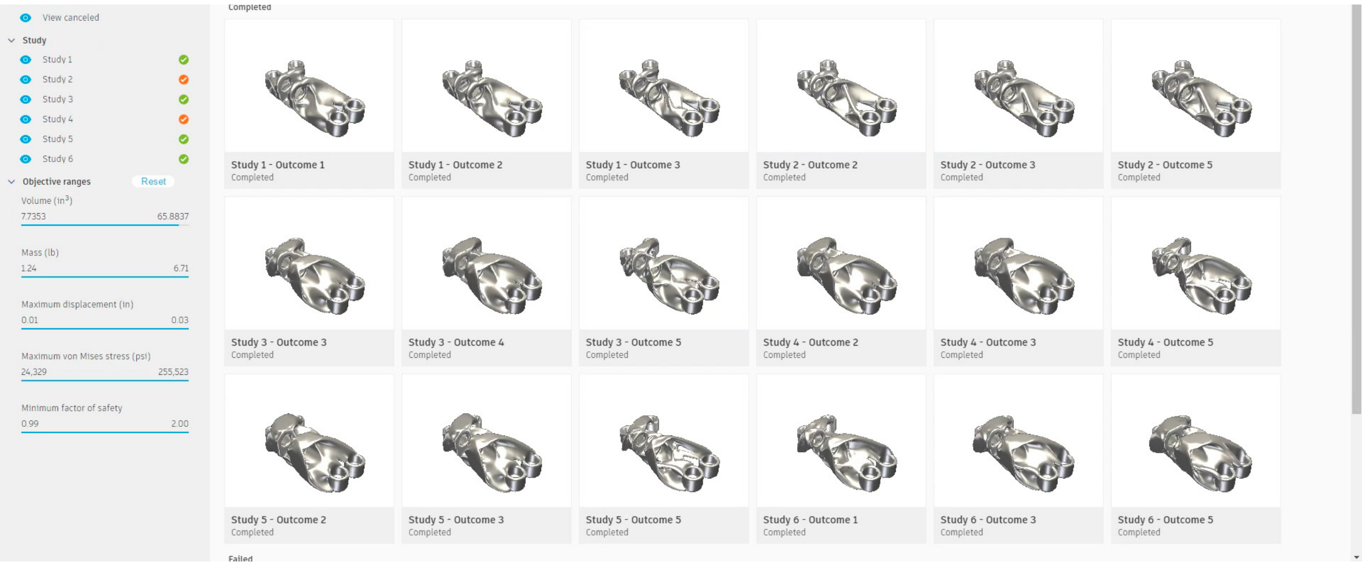

Figure 66: Various generated designs in Fusion 360[69]

8.7. Conclusion

Dassault Systèmes has a multitude of CAD applications which claim to implement a generative design process. Unfortunately, this is not true according to Table 8 because all software miss various specifications before it can use a generative design process. Especially the creation of multiple results and adding material are missing.

This entails that SME's have no access yet to software that incorporates a generative design process. A wide variety of professional advanced CAD software is available for SME's but each software has its flaws or shortcomings.

But more importantly, it seems CAD companies are focusing right now on other areas such as the digital twin, building information modelling and putting their products in the cloud[70] while generative design is on the back burner. Although many programmes have the term integrated in their naming convention, it is clear that work needs to be done. The first step would be a clear understanding of the definition of generative design and incorporate it in the company. As of 2020, Dassault Systèmes released an eBook[71] with their definition of generative design which is incomplete and incongruent with the definition researched in this thesis. Their definition is the following:

"Generative Design systems allow the formation of complex compositions, both formal and conceptual, through the implementation of a simple set of operations and parameters. Changing a parameter will regenerate your design automatically, offering a new set of elements and geometries to work with.[71]"

	Solidworks Simulation	xDesign	Functional generative design	xGenerative design	*Siemens*	*Autodesk*
Nonstructural parameters			✓		✓	✓
Iterative algorithms	✓	✓	✓		✓	✓
Remove and add material		✓		✓		✓
Incomplete CAD model		✓				
Accurate CAE analysis	✓		✓		✓	✓
Multiple results				✓		✓
AM controls	✓		✓		✓	

Table 8: A comparison between CAD software packages using the generative design specifications

PART

Results

III

Chapter 9
Revision of the research question

The results of Part II indicate that the research question as defined in Chapter 1 is difficult to answer due to the current state of generative design. This chapter makes a revision to the research question.

Chapter 10
Roadmap

All the results gathered in Part II are visually explained in one visualisation. This chapter shows the roadmap and explains it in further detail.

Chapter 11
Conclusions and recommendations

This chapter gives a final conclusion to answer the revised research question and gives multiple recommendations for future work.

Chapter 9

Revision of the research question

In the previous chapters, I used a variety of research methods to research if generative design can already be used by SME's in combination with FDM printers. In this chapter, I will explain that this is not yet possible and I am not able to answer my research question. Which is why I will adjust my research question to explain why it is not yet possible and how this can be resolved.

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9.1. Revised research question

The conclusions drawn from the research methods in previous chapters show that the current state of generative design is not sufficient for introduction to SME's. It is possible to introduce the concept but actual implementation is not recommended. To do so right now would only create aversion against the method due to the difficulty of the current software and the ambiguity of the definition. Thus, the research question stated at the beginning of this thesis is unfortunately not yet relevant at this point in time.

However, the research and knowledge gathered in this thesis can help with assisting the implementation of generative design in current CAD environments, the market and introduce the term to SME's in general. The research question will be transformed such that the information gathered can be utilised to assist the market in implementation of generative design. The research question will be revised into the following question shown on the right page:

This new research question will give an answer to which actions the participating parties have to take. The parties involved in implementation of generative design are the current CAD market, SME's and software developers. Each party has to make adjustments to incorporate generative design in current design processes. Why these parties were chosen is explained in Chapter 10.

Which actions are required to make generative design viable for SME's to use in combination with FDM?

Chapter 10

Roadmap

This chapter I will summarise visually the actions that need to be taken in order to incorporate generative design successfully in SME's. I made a roadmap that involves three different parties, namely SME's, software developers and researchers. I will use this roadmap to answer the revised research question.

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10.1. Interpretation of results

The results of the research methods were different than expected at the beginning of this thesis. As is reflected in the revision of the research question in the previous chapter.

In the beginning, the intent was to produce a practical deliverable in the form of design rules which SME's could use to produce generative designs with FDM printers. Additionally, a theoretical deliverable about the future of generative design would be added to address any flaws in the generative design method. However, after a while it was discovered that commercial generative design programmes were not in a status which could implement a generative design method. Thus, the practical deliverable was not relevant yet.

The choice was made to make a roadmap that is in essence preliminary research for the initial research question. This roadmap shows a variety of actions over time which need to be completed before generative design can be used by SME's. The amount of time each action takes is difficult to estimate so the time frame can vary between three years to twenty years, but the sequence of actions is correct. Although this might change in the future. The roadmap is displayed on the next page spread in Figure 67.

10.2. Involved parties

A decision was made to only involve three main parties in the roadmap due to a variety of reasons. The parties are SME's, software companies and researchers.

First of all, the research methods used in this thesis directly involve these parties. For example, the market research involves mainly the SME"s in addition to the software companies. The literature research involves researchers and software research is of course connected to software companies. Knowledge about these parties are thus the greatest and made sure that the suggested actions in the roadmap are relevant and correct.

Secondly, these parties have the most influence on SME's to incorporate generative design in their process. Another big party could maybe be the general CAD market. However, the CAD market is a very ambiguous term and could be divided in multiple parties which would not be relevant. Furthermore, the CAD market cannot actively take an action. The market is more a result of the actions taken by companies or governments so it is difficult to influence directly. Due to these reasons, the decision was made to omit the CAD market from the roadmap.

Lastly, the amount of parties which are involved is substantial. A conscious decision was made to limit the parties in order to reduce the scope and size of the roadmap. The reason to omit a party can differ. For example, governments can have a huge influence but are such intricate parties that the suggested actions in the roadmap could be wrong. Furthermore, smaller parties only have a very limited influence on SME's and their actions would not of much significance.

10.3. Diagram choice

The diagram of choice to display the roadmap is a variety on the flowchart. Each party has its own vertical linear flowchart. The reason to use this diagram is because a linear flowchart represent a sequence of actions which need to be followed in a certain order.

The roadmap variates slightly from a regular linear flowchart because the flowchart from a party can influence an action of another party. Furthermore, the three linear flowcharts all result in the same ending which is unusual.

Roadmap

This roadmap illustrates necessary actions certain parties need to take before it is possible to incorporate generative design processes in SME's.

Each party has a line of actions which they are responsible for and have to execute. Some actions have influence on an action of another party.

Each action has a number appointed. This action is explained in more detail in the following sections with a corresponding number.

The actions are on an time-axis but the amount of time it takes to complete all actions is difficult to estimate.

Legend

Indirect influence on action

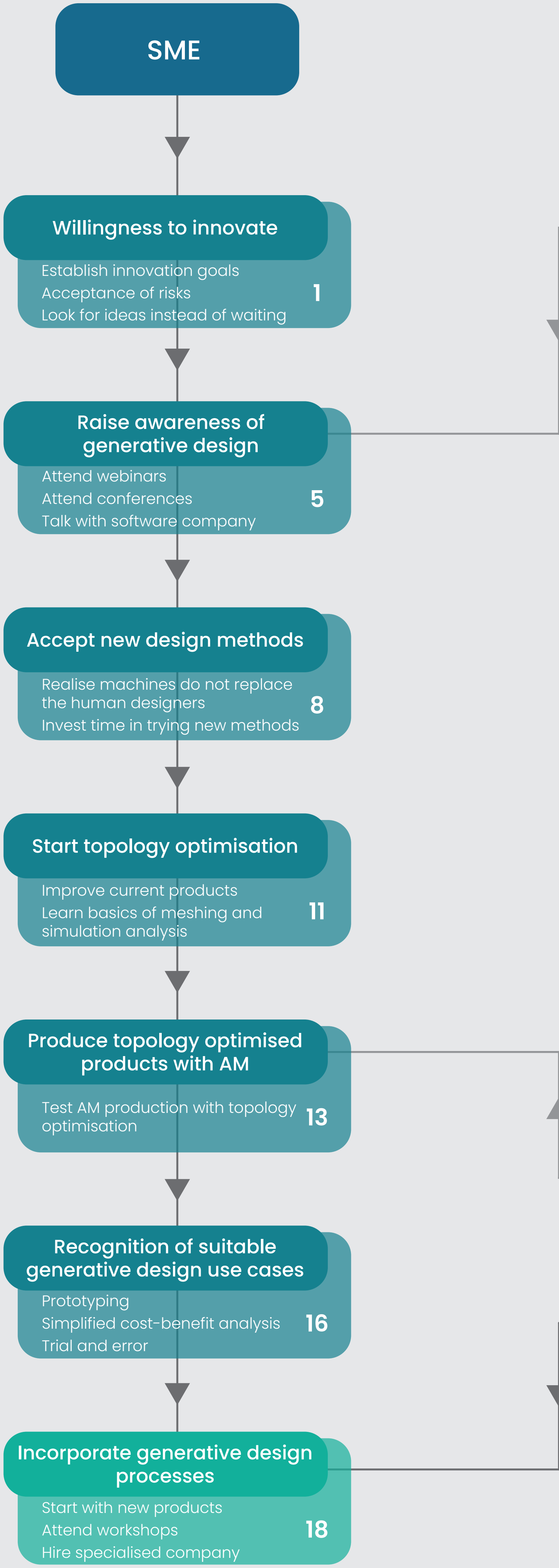
Next action

Party

Action

Suggestions

End



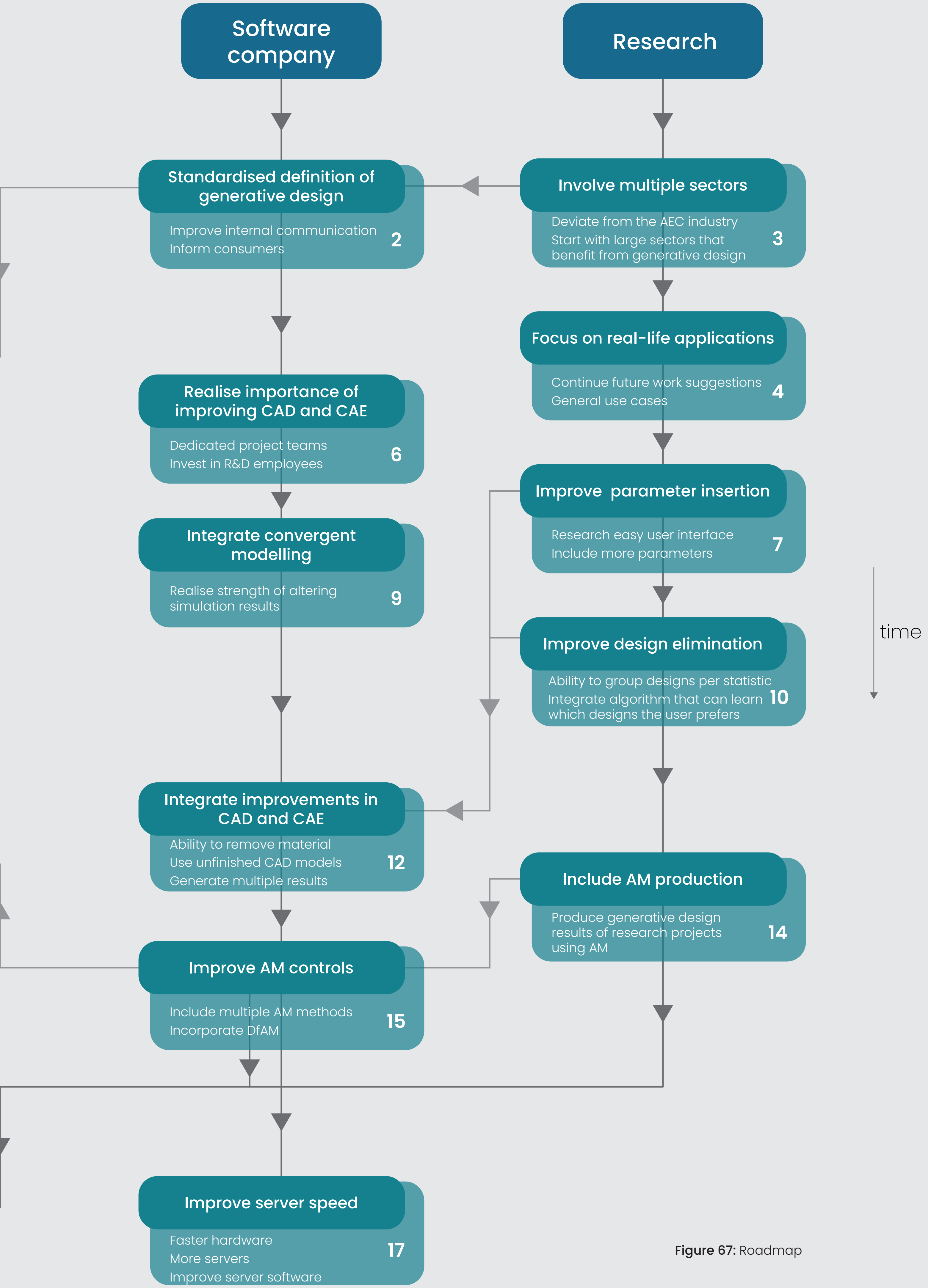


Figure 67: Roadmap

10.4. Substantiation

The roadmap visually shows which actions need to be taken to start incorporating generative design processes in SME's. The following sections have a number corresponding to an action on the Roadmap in Figure 67.

The actions which are involved are based on the results of the research methods in Part II. Although more actions could be taken to incorporate generative design in SME's, the decision was made to only involve actions based on results of the research. These actions have a good basis on why they are necessary and are of the upmost importance.

10.4.1. Willingness to innovate

SME's are always open to innovation when asked, such as the market research in this thesis, but in reality, they are not as willing as they claim. SME's are fairly resistant to change if it involves changing their traditional processes. Especially when it involves effort on their side.

The CEO of CAD2M has experienced this many times when trying to sell their 3D printers in which companies are very enthusiastic at first but change their mind when they need to adjust their method. SME's need to be open to innovative methods and realise the pros in addition to the cons they experience in the beginning.

The establishment of innovation goals and accepting certain risks or hiccups is a great first step.

10.4.2. Standardised definition of generative design

Multiple companies still do not understand the true definition of generative design and mostly use it as a buzzword in their software. Companies misunderstand its true definition and a variety of definitions exist in the current market. Furthermore, the definition can even differ between software packages from the same company. A decision must be made among companies for a standard definition of generative design to prevent misunderstandings among consumers.

Researchers already have a good grasp on the definition, as seen in Chapter 3, but need to communicate this to the software companies as well which is part of the following action.

10.4.3. Involve multiple sectors

Research into generative design is currently very limited and mostly done in the AEC sector. In the opinion of the author, generative design could be even more valuable in large sectors such as the automotive, aviation or the manufacturing industry. To improve the generative design method, researchers should involve other sectors as well so other parties can learn more about generative design and how it could improve their industry sector.

Their findings should be communicated to all sectors so software companies can have a clear understanding of the impact it could have on their software. Even better, an understanding on how to incorporate it correctly in their software packages per industry sector.

10.4.4. Focus on real-life applications

Research in generative design applications is limited and is mostly focused on researching the problems than actually realising solutions. At this point, it has been proven that generative design could offer solutions in the CAD world but no researcher has actually tested it in a wide-scale test.

To actually progress in generative design, researchers should focus on generative design applications which will actually be used in real-life. Researchers need to apply their knowledge and make solutions instead of analysing the problems it can solve or create.

This could be achieved by learning from their results in previous research and start with research on the future work recommendations.

10.4.5. Raise awareness of generative design

The need to know about the current trends in the manufacturing industry is low for SME' as mentioned in 10.4.1.. They need to raise their awareness of new trends in the industry to gain knowledge about generative design and other innovations.

While several companies have heard about generative design, they are uncertain about the specifics. This is also due to the fact that software companies do not have a standardised definition of generative design yet. An SME could set aside some time for employees to attend webinars, conferences or talking with representatives of software companies when the definition of generative design is clear and coherent with other companies.

10.4.6. Realise importance of improving CAD and CAE

Some companies are at the time of writing more interested in either bringing their programmes to the cloud or are focusing on industry 4.0. Improving the CAD and CAE seems to be on the back burner or forgotten. For example, Autodesk had their project Dreamcatcher which studies generative design. But it seems canceled because no progress has been published since 2017.

To make strides in generative design, it is important companies realise that strides can still be made, especially concerning generative design. Especially the AI of the CAD and CAE programmes can be improved. Also, the manufacturing controls for AM are very limited so design rules for AM also need to be improved.

10.4.7. Improve parameter insertion

It is difficult to use the currently available parameters to develop an accurate problem presentation. A lack of variety in parameters of the software is one problem. Most parameters are limited to geometrical or physics based parameters such as forces or thermal conditions. Furthermore, the interface to insert certain parameters can be confusing for the user. Designers might find it difficult to define the restrictions and requirements of the desired product. This can result in undesired product characteristics.

Generative design, which requires accurate parameter insertion to achieve the desired results, needs more variety in the amount of parameters. Additionally, an improvement of the parameter insertion method is necessary.

A more intuitive user interface needs to be researched while new algorithms need to be developed to consider more parameters. Researchers can analyse several industries to see which parameters are most requested.

10.4.8. Accept new design methods

Humans in general dislike change, so accepting new design methods that changes the current workflow is difficult. Especially employees in more traditional companies who have done the same job for multiple years are hesitant.

An extra aversion exists for generative design because the work is done by computers. Employees feel that they are being replaced while in reality generative design is just an additional tool in the CAD toolbox.

SME's could implement trial periods in their production process. This could be used to try new CAD tools or just experiment in general with new design methods.

10.4.9. Integrate convergent modeling

Generative design results are often difficult to adjust and the designer is stuck with the result the software gives him or her. The designer could create a new design and try to copy the generated design while implementing the desired change. However, this would take up time and is difficult to achieve.

Convergent modeling, which Siemens NX has already integrated, would alleviate this problem. This technique combines the mesh and the solid into one model which allows designers to adjust the design.

If all software companies would integrate convergent modeling, designers would have the ability to adjust generated designs to their liking and greatly improve the easy of use of generative design.

10.4.10. Improve design elimination

Generative design can give designers thousands of iterations for one problem. Designers can experience decision fatigue after sorting through all of them. Research should be done for an optimum user interface which will recognise viable designs and can already pre-sort designs for the designer.

Examples could be developments such as a ranking system. Users can indicate if they like or dislike a certain design. An artificial intelligence system can recognise what kind of designs are liked by the user and present similar design. Meanwhile, designs similar to the disliked designs will be moved to the background or just removed.

Another solution could be a dashboard in which graphs or visual representations can present information to the user. The user can use filters to only show designs which meet certain conditions or look at graphs to compare designs.

10.4.11. Start topology optimisation

SME's can prepare for generative design by experimenting with topology optimisation, a tool that is integrated in a variety of CAD software already. It will familiarise SME's with the process of optimising designs and inserting different parameters for a correct simulation. Furthermore, they can learn to understand the basics of meshing and simulation analysis before trying generative design.

While this might seem like an unimportant action, it can influence the acceptance rate of generative design because the process is similar. You begin with parameter insertion, followed by simulation and you end with an analysis of the results. Users get familiar with the process and the learning curve for generative design becomes less steep.

10.4.12. Integrate improvements in CAD and CAE

The various developments and progress of researchers should be integrated in CAD software. While CAD software companies have their own R&D departments, they can still learn much from researchers. Especially regarding design elimination and parameter insertion.

10.4.13. Produce topology optimised products with AM

Similar to action 10, this action is mostly preparation to increase the acceptance rate of generative design. After experimenting with topology optimisation, the results need to be produced with AM. Topology optimised products are difficult to produce with traditional manufacturing similar to generated designs. Experiencing what kind of products are feasible to print and which products will result in failure, can prepare users for generative design products. Employees gain enough knowledge to judge generated designs on their viability for success in FDM.

10.4.14. Include AM production

AM makes it possible to produce generated designs but researchers fail to include this very important step in most research papers. Although they do mention AM, it is often a neglected subject in their research methods. Involving AM production in their research projects could help to improve and establish actual AM design rules in CAD software.

Furthermore, the feasibility of AM production in generative design needs to be tested. Intuition indicates that, in the current state of AM, generated designs are only feasible for small scale production. However, with research the possibilities of AM in combination with generative design might increase.

10.4.15. Improve AM controls

In its current state, CAD programmes are unsuccessful in creating models which can be manufactured using FDM. Several factors such as a lack of AM design rules parameters, missing common AM materials such as thermoplastics and missing AM methods prevents CAD software from optimising designs.

Software companies should improve the AM controls by making several adjustments. Examples are differentiating between AM methods and implementing corresponding design rules. Each method has slightly different design rules and as of right now, CAD software sees AM as one process instead of multiple processes.

10.4.16. Recognition of suitable generative design use cases

Generative design should not be used for each design case. It could be that the desired result is an existing design with less mass in which case, topology optimisation delivers a better result.

Additionally, SME's should recognise which design cases could use generative design to reduce lead time. For example, an SME is at the beginning of the design process. Generative design could help by giving several design suggestions at the beginning which adhere to the design requirements. SME's can choose one design and iterate on it.

Because design cases can vary a lot between companies, it is dfficult to give a golden rule. However, companies can try a cost-benefit analysis or trial and error to discover in which cases generative design could help and in which cases it is obsolete.

10.4.17. Improve server speed

Large assemblies, or even small models, are simulated using servers of the CAD software company. The servers are often very slow and, depending on the size of model or assembly, may take several hours or even days. For generative design, which is more suitable for smaller models, it is a serious disadvantage. Instead of only simulating one model, the programme also has to calculate several iterations and simulate those as well. Generative design would become more attractive if more servers were available or if hardware and software became more efficient to do those calculations. While this action is not necessary for the success of generative design, it could reduce hesitant adopters.

10.4.18. Incorporate generative design processes

After all the preparation, it is time for SME's to start incorporating the generative design process in addition to their usual traditional design process. SME's are prepared and the CAD companies, with help from research, have improved their software. At this point in time, generative design should be user-friendly, involve AM methods, have multiple new non-geometric parameter possibilities and have a productive way of design elimination.

Chapter 11

Conclusions and recommendations

In this chapter, I will combine all knowledge gathered in the previous chapters and present my conclusion. I will answer the revised research question and present recommended future work which will fill in the gaps of my research.

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11.1. Conclusions

The initial goal of this thesis was to provide a bridge for the gap between SME's and their knowledge of generative design. It would allow SME's to begin experimenting with generative design and produce the generated results using FDM printers. The research methods used during the research phase proved that generative design is insufficient in its current state in contrast to opinions of CAD companies.

The research methods did provide enough knowledge to ascertain what needs to be done before starting to incorporate a generative design process in SME's. Thus, the research question was changed to discover which actions need to be taken before generative design becomes a viable option for SME's in combination with FDM.

A roadmap was made that shows software companies, SME's and researchers the necessary actions they have to take before realisation. Each party has one main action they need to take before generative design can become a viable option for SME's:

- *SME's need to be more open towards innovation.*
- *Researchers should focus on actually realising solutions for real-life applications instead of focusing on the problems.*
- *A consensus should be made in the industry what the standard definition will be of generative design.*

In conclusion, it will take some time before generative design becomes a viable solution for SME's. In its current state, generative design is too difficult to integrate and it will cause more problems than it will provide solutions. However, if actions are taken to improve generative design, I will have no doubt that it will prove to be a powerful tool for SME's in the future.

11.2. Recommendations

Although this thesis provides a general roadmap, certain limitations such as the COVID-19 pandemic and limited access to CAD software reduced the scope of the research. Furthermore, several ideas were not incorporated into the research due to limitations in time and the eventual revision of the research question.

A valuable addition would have been more in-depth research into the current design processes of SME's, which was the initial plan. Due to COVID-19, this was not a possibility and the data gathered from SME's were limited to phone interviews with employees.

Furthermore, only professional CAD software packages by Dassault were tested. Future work could incorporate other professional software in addition to open-source or more experimental software packages. Maybe smaller unknown companies exist which succeed in incorporating a basic generative design process.

It would be interesting to do research in actually incorporating some of the actions suggested in this thesis. While suggestions are given on how to incorporate them, it is not proven if they are suitable.

The time spent on producing generated designs of FDM prints were also limited due to the switch in the research question and working from home with limited access to FDM printers. Researchers could maybe try to develop and research algorithms which incorporate AM limitations in CAD.

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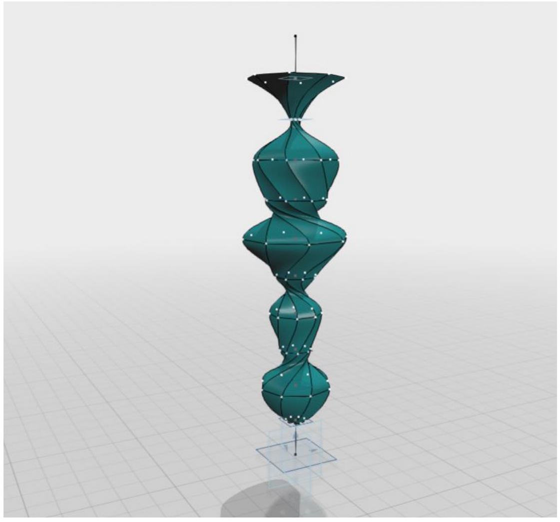
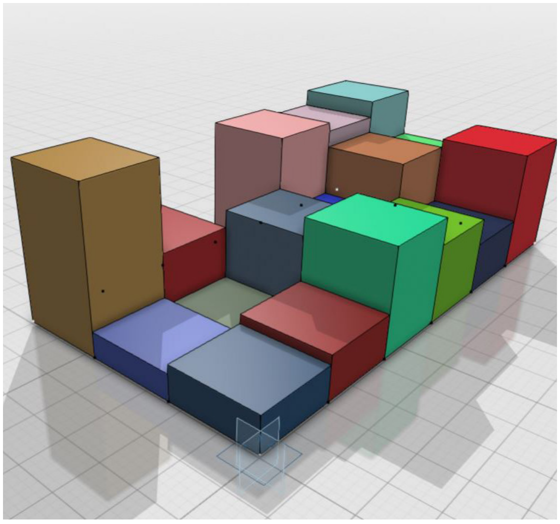
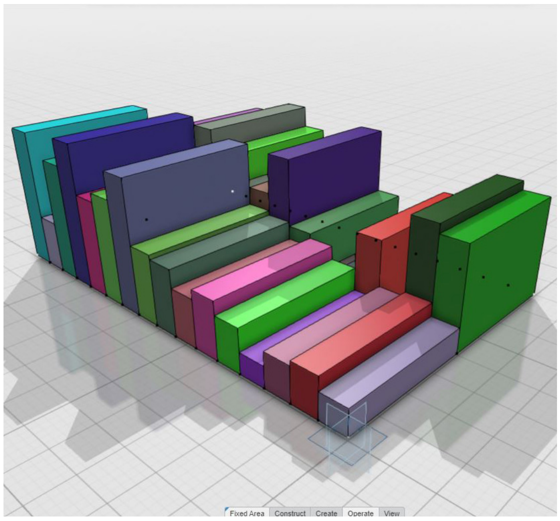
Appendix A

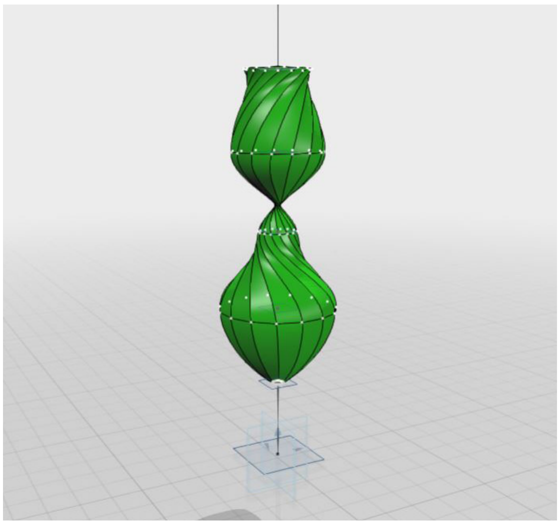
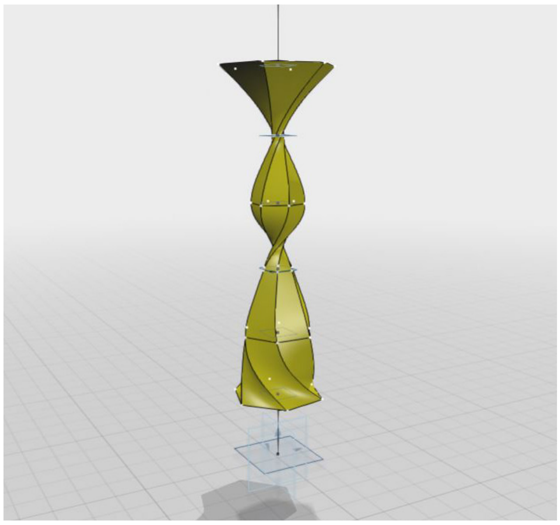
The specifications list of the Dddrop EVO Twin[72].

Features	Dual printhead (twin): up to 300°C.
	Smart: Remote control via phone/tablet app or browser from anywhere in the world, printing via USB/WiFi/LAN.
	Filament Management: Automatic switch to a full reel when out of filament for continuous printing or pause and messaging on filament problems. Never lose a print because no filament or entangled filament and always use up your entire reel!
	Temperature controlled print room: Fully controlled print room keeps warping at bay, especially useful when printing more high-tech materials.
	Swappable buildplate: Swap your buildplatform easy for different printjobs and materials.
	7 inch full color touchscreen
	Next generation CPU (computer processor unit)
	Next generation printer control
	Camera
	LED light
Printer dimensions	530 x 660 x 570 mm (WxDxH)
Build volume	330 x 310 x 305 mm (WxDxH)
Heated print bed	130 °C
Max. printing speed	150 mm/s
Print layer height	0.05 – 0.75mm
Nozzle diameter	0.2 – 0.4 – 0.6 – 0.8 – 1.0 mm
Nozzle material	(optional) Brass or Stainless steel
Materials	PLA,ABS,PETG,FLEX,HIPS,PVA,PA(Nylon),PC,PP,Metal-,Carbon-and Wood filled, and more… 1.75mm open filament system.
Inclusive	• One year silver support contract • One year professional helpdesk • Starter kit: Tools, 2x 1kg PLA filament, nozzles and extra print table glass

Appendix B

Several more generative design creations in xGenerative design.

Appendix C

Interview flow for customers of Dddrop printers.

Goede...,
u spreekt met Claudia Westerveld namens Dddrop printers en CAD2M. Als het goed is bent u klant van ons en maakt u gebruik van de Dddrop printers, klopt dat?

==============
In samenwerking met de Universiteit Twente en Dddrop printers ben ik bezig met een onderzoek om generatief design in combinatie met 3D printen sneller en makkelijker beschikbaar te maken voor bedrijven zoals die van u.
===============

Weet U toevallig wat generatief design betekent?

Nee: Generatief design is een proces waarbij software op basis van algoritmen zelfstandig ontwerpen genereert. Designers voeren daarbij vooraf zoveel mogelijk variabelen in. Bijvoorbeeld de grootte, de kracht die het product moet kunnen verdragen, de omstandigheden en het beschikbare materiaal, maar ook zaken als kosten- en materiaal beperkingen. Algoritmes berekenen vervolgens razendsnel duizenden mogelijke ontwerpen door. Het kiest daaruit de modellen die het beste voldoen aan de vooraf gestelde eisen. Voordeel daarvan is dat je binnen een paar minuten duizenden designs hebt die voldoen aan alle eisen van de gebruiker.
Ja: Ga verder

===============
U zou mij heel erg helpen als u een aantal vragen zou kunnen beantwoorden over hoe u 3D printers gebruikt en wat jullie verwachten van 3D printers in de toekomst en generatief design.
===============

Zou het u schikken om nu een kleine 15 minuten mijn vragen te kunnen beantwoorden? U zou mij daar heel blij mee maken. Als het nu niet schikt, zouden we dan een telefonische afspraak op een ander moment kunnen inplannen?
Nee: Zou ik u dan .... terug kunnen bellen?
Ja: Ga verder
===============

Algemeen
In het kort, wat doet uw bedrijf precies?
....
Hoeveel werknemers werken er ongeveer bij uw bedrijf? Hoeveel werken er met CAD?
....

Welke CAD software gebruikt u en wat voor software gebruikt u voor de 3D printers?
....

3D printen
Waar gebruikt uw bedrijf voornamelijk 3D printers voor?
Prefereren jullie snellere prints met lagere kwaliteit of langzamere prints met hoge kwaliteit? (bevestigingsvraag)
Doen jullie nog veel post-processing aan het product? Schuren, support materiaal afbreken etc.?
....
Waarom hebben jullie voor deze manier van 3D printen gekozen? Bijvoorbeeld plastic i.p.v. metaal?
....
Wat zijn aspecten van 3D printen waar u tegenaan loopt?
....
Wat voor voordelen levert 3D printen uw bedrijf?
....
Past u wel eens instellingen aan in de slicer?
....
Wat voor materiaal gebruiken jullie het liefst en waarom?
....

Software
Waarom gebruikt u CAD Software pakket ... en niet andere software pakketten?
....
Maakt uw bedrijf gebruik van add-on software die niet van Softwarepakket X is? Zo ja, welke?
....

Generatief Design
Heeft u (of collega's) ooit met generatief design gewerkt en zo ja, met welk software pakket?
....
===============

Ja:
Waarom heeft u het gebruikt?
....
Hoe ervaarde u het om generatief design te gebruiken?
....
Wat vond u positief werken?
....
Wat vond u negatief werken?
....

Nee:
Zou u er ooit gebruik van willen maken? (eventueel generatief design opnieuw uitleggen)
......
Waarom wel/niet?
......
Wat zou voor uw bedrijf de meeste toegevoegde waarde hebben?

1. Honderden designs binnen een paar minuten die voldoen aan de ingevoerde eisen
2. Een geoptimaliseerd product qua gewicht en kracht
3. Producten die meer creatieve vormen hebben

Waarom heeft u voor dat antwoord gekozen?
....
================

Dit waren al mijn vragen. Hartstikke bedankt dat u mij hiermee heeft willen helpen. Zijn er nog vragen aan uw kant?

Nogmaals heel erg bedankt en ik wens u nog een fijne dag. Tot ziens!

Appendix D

General interview results of the clients of Dddrop 3D printers.

Company	Branch	Size	Use of AM	Why FDM	Pros AM
1	Plastic extrusion	Medium-sized	Prototypes, representation of final product for clients, tools	Cheap	Better estimation of the design before final production
2	Healthcare	Medium-sized	Moulds	Cheapest method, because we break our moulds.	Cheap and able to produce moulds if casts are too painful for patient
3	Foundry	Medium-sized	Product presentation for clients and tools	Cheapest method and metal printers are not as accurate as casting	Products become tangible in a quick way for our client in a cheap method.
4	Precision mechanics	Small-sized	Moulds, prototypes and tools for own machines	FDM is cheap and works	It is easy to produce products quickly, but it is not necessary for us
5	Blinds and awnings	Small-sized	Printing adaptations for systems within blinds and awnings	We use it for plastic products and FDM is cheapest and easiest.	Can provide all systems with a printed adaption so the motor works.
6	Police	Unknown	Cases for electronics and reconstructions for research.	Quick and operational	Quick and fairly accurate production
7	Machine industry	Medium-sized	Use a metal printer for production. An FDM printer for proof of concepts and for tools.	The FDM printer was for us an addition to our metal printer.	Quick proof of concepts and supporting production. Plus goodwill for colleagues by printing things for home.
8	Media technology	Unknown	We used it to produce plastic housing for our products.	We choose FDM because our cases are made from plastic.	Ability to create quick products to see what it looks like.
9	Plastic consumer products	Medium-sized	Product development, assembly tools		Easy and cheap model making
10	Art	Self-employed	Prototyping, small production batches		Flexibility, price

Cons AM	Adjust settings in slicer	Preferred material	Aware of generative design	Would you like to use it?	Multiple choice: most added value
The accuracy and precision is still too low	Colleagues sometimes do, but preferably not	PLA, ABS, PET-G. PLA is the easiest for us but with PET-G we get good results	No, some younger colleagues have heard of it	Yes and no, it can help us but I don't know if it works with our production method of extrusion.	B
Size of printer is too small and big products often fail	No, only infill and brim we sometimes adjust	PLA because it just works	No	Yes, for the ability to adjust parameters to optimise prints for each patient	B
Only the printer itself, the process is fine	Sometimes we try to adjust settings but often we use the pre-set	PLA, it is the easiest for us	No	Maybe in the future, as of right now we simply don't have the time to implement it. GD can make our products more attractive for clients due to less material, thus cheaper.	B
Nothing, everything just works	Yes, simple settings like the nozzle size and infill but that's it.	PLA, because it is easy and ABS for the heat resistance.	No	Not really relevant for us because we make such small products.	B
Only problems with the printer itself due to older printer	Yes, but only simple settings like a brim	ABS because of its properties	No	Yes, if it deliver the pros is promises and is easy to implement.	B
The accuracy is too low and speed may be quicker	Yes, but only simple settings like infill and temperature.	ABS because it is better resistant to light	No	Not really relevant for our branch because we make reconstructions which do not need to be optimised or have creative shapes.	A
Foodgrade prints are difficult due to dirt clinging to the print which means it cannot be used in certain environments.	No	PLA or PET-G	Yes, I encountered it during a training but never used it after it.	Yes, but I don't know if the extra work and costs will weigh up.	B
The surface quality could be better.	Sometimes, but not often	ABS	No	I don't have enough information to decide, but I would like to try it and see its capabilities.	Unknown
First think about what you want to make and then choosing printing method	Preferably not, I would like pre-sets	ABS for its strongest properties, PLA for quick prints	No	Yes, we are open for new engineering experiences	B and C
Resolution, size	Always	PLA(easy), ABS(sturdy, properties)	No	Yes, it seems like a next logical step in CAD modelling	C