Designing for 3D printing with non-proprietary software

Non-proprietary software are open-source and free software

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Abstract:

In the field of 3D printing model design, it is essential to master the necessary ideas that govern good modelling production. There are many things that need clarifying in this relatively new technology and as it is also available to non-professionals, who work with it at home rather than in industry, educational material that is enlightening the general public, is of significant value. Note: non- proprietary software is the focus of this study, as it is available to all, regardless of financial resources. After a general introduction into the world of 3D printing, this thesis delves into the subtleties of a range of CAD software dedicated to 3D printing to reveal the different functions and methods they employ, of which two products are chosen for making a comparison: Blender and SolidWorks. The features and functions of both products are explained and the reason for choosing them; for example, Blender is open source while SolidWorks is not but is a product, which has a full-version that is used industrially. Both software products have been employed by the author to create an identical model to reveal the practical advantages of each of the software's features and functions. At each stage of the modelling process; CAD design and production, which includes slicing, the results have been thoroughly analyzed. SWOT and AHP were used in the theoretical analysis of the two software products. This thesis is an enlightening guide, to revealing the hidden and subtle points that need to be considered when choosing the most appropriate CAD software available for 3D printing.

Keywords:	3D Printing, CAD software, open-source, Blender, SolidWorks, SWOT, AHP, business card-holder, free of charge.
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Foreword

Firstly, I wish to thank my thesis supervisor Mathew Vihtonen for his excellent guidance during the making of this thesis, as well as all the personnel of Arcada University of Applied Sciences that accompanied me in the process of achieving my first higher education.

I would like to express my great gratitude toward William Patrick Parsons, an extraordinary friend that I am blessed to have. You have broaden my horizon and promoted my potential, both in professional career and personal contexts.

Last but by no mean least, my appreciation extends toward my family and friends, whose continuous encouragement have helped me through the difficult time, without you, none of this could have ever happened.

Finally, I wish all who read this thesis enjoy what they discover in it the same way it gave me pleasure as it evolved when creating it.

1 INTRODUCTION

1.1 Background

Though not many people have any idea when the term "3D printing" is first mentioned, this technique of rapid prototyping has been emerging for more than 30 years and ultimately been giving innovative changes to every industry it touches [1].

The history of 3D printing or additive manufacturing can be traced back to the 1980's when Hideo Kodama established a rapid prototyping, which builds up layers bound by the perimeter of the cross-sectional slice in the model [2]. It was not until 1986 that Charles (Chuck) Hull obtained his patent for the ancestor of 3D printing with the invention of Stereolithography Apparatus (SLA) [3]. The mechanism of SLA can be defined as a method of using a UV laser beam to penetrate a container of liquid photopolymer, and the liquid that is at the focal point of the light beam will be turned into solid plastic then in that way be moulded into shape. Later in 1987, Carl Deckard filed for a patent for the selective laser sintering (SLS), which uses a powder instead of a liquid as is used with SLA [2].

The birth of 3D printing was, needless to say, a ground-breaking discovery at the time but still there was a need to perfect better printed results as 3D printing was still in its infancy.

From the 2000's onward, the formidable growth of 3D printing has not fail to surprise the public, many of whom have had their eyes on it from the outset. In 2006, a team of Scientists from Wake Forest Institute (USA) had successfully printed the scaffold of a human bladder, filled with human cells and later implanted in a patient's body [4]. Following this success, functional kidneys, prosthetic legs or bones and even blood vessels have been structurally printed from degradable polymer and/or human cells, opening new branches for regenerative medicine, and most importantly, giving hope to thousands of patients, whose lives are otherwise depending on donated human organs [4].

From 2010 until now, the technology has advanced immensely, printing quality has improved down to nano-scale, and printer-costs have become more appealing to the interested folks as competitions start to rise.

As to the convenience the technique can bring, it is now used in a wide range of diverse industries, including automotive, aerospace, defence and healthcare. More and more, it is disrupting traditional manufacturing, as prototyping costs significantly decrease, created in a non-traditional factory environment without the need for machining tools, and from an economical scale, and there is no time wasted getting the product the customer [5]. Given these points, the situation can be summed up by a quote from a New River College's document "3D printing changes the calculus of manufacturing by optimizing for batches of one" [6].

1.2 Objectives

Today, there are many CAD (Computer Aided Design) programs to choose from, to fulfil the purpose of visualizing an object in three dimensions before printing. Each and every one has strong points to offer and also, on the down side, disadvantages for users to take into consideration.

This thesis mainly focuses on small-scale targeted users such as hobbyists, students, enthusiasts or small to medium companies, who do not feel the need to have professional, industrialized, pricey software that requires extensive skills to implement it. Thus, the thesis proposes the use of alternative open source software options that are free of charge, to perform the same tasks as licensed software would do, and, in addition, they come with a helpful broad learning forum provided online.

Given these points, this thesis work aims at achieving the following objectives:

- To identify available non-proprietary (free and open source) design software.
- To design the same product using both Blender (open source software) and SolidWorks (licensed software).
- To 3D print the products and compare these two software in terms of designing and applicability for 3D printing.
- To analyse the applicability the two software using SWOT and Analytic Hierarchy Process (AHP).

2 LITERATURE REVIEW

2.1 Designing with software

3D printing can be perceived as its name implies: making (by the act of printing) a three dimensional object. Though the science and process behind 3D printing may vary as it has tremendously developed during recent years, all 3D printing objects are started with a digital file.

A relevant digital file for 3D printing can be achieved either by collecting data from a 3D scanner, which takes successive pictures of an existing object, from different angles, to recreate a 3D version of it on the computer or using CAD (Computer Aid Design) software. If a 3D scanner attempts to replicate real life objects, a CAD modelling software can convert ideas into virtual design and later can be modified to suit any post-designing purposes [1].

As stated earlier, the possibilities that CAD software offer are only limited by the user’s creative ideas and imagination, set of skills, but most of all, the availability of the CAD software they choose to use. There are a variety of CAD software products on the market, some are industrial-grade software such as SolidWorks, PTC Creo or Siemens NX, which initially costing thousands for a license, with the additional annual subscription fees, adds-on fees and so on.

When the list of choices above does not seem to appeal, understandably, to hobbyists or non-designers, the open source software option is there to satisfy the urge to become familiar with modelling software that offers a comprehensive set of suitable tools, fits a modest budget, yet still covers the requirements of all levels from the raw beginners to the very accomplished.

2.2 Open source software

A software mainly functions through the source code that is written by computer programmers, by changing the source code, a programmer can improve software to perform better “by adding features to it or fixing coding that does not always work correctly”. “Open source software is software with source code that anyone can inspect, modify, and enhance” [7]. Open source software creators allow their product to be freely available and publically distributed, and by ‘product’, it means the whole package including right of use, source code and right to alter the code. WordPress, Mozilla Firefox, Audacity, 7-Zip and Blender are example of open source software.

All of us who are not programmers but computer users have been using proprietary software or “closed software” which can only be legally copied, inspected and altered by their original authors. The creators of proprietary software have the exclusive control over how the software functions, and user must agree by signing the license before using it [7]. Some typical proprietary software are Microsoft Office, Adobe Photoshop, SolidWorks and Siemens NX and so on.

In the order to attune with the object mentioned in this thesis, the term “software” is understood as CAD modelling software and “open source” mostly refers to software that are free of charge, the users have no binding fee or contract when using the software. It follows that some of open source software reviewed during the thesis may not have their source code shared; however, programming is not the main matter of concern here.

2.3 3D Slash

The 3D Slash creator team, which is led by the CEO Sylvain Huet, has advertised their software as “A 3D piece of cake” and it really lives up to the slogan.

3D Slash is considered to be one of the easiest 3D modelling software to use in the market, the software is said to be inspired from the kid game Minecraft, where the user builds up block after block of material and slash them with several tools to create the desired shape [8]. 3D Slash offers an intuitive, original experience with fun interface like playing a game and creating sophisticated 3D design with much less thought than actually building one from scratch [9]. It serves a huge-market audience, in direct connection with well-known platforms (Sketchfab and YouMagine for storing design, 3d Hubs and Sculpteo for local printing services, Thingiverse and 3dfilemarket for customizing and printing) thus providing an ideal solution for non-designers taking their first step in learning a 3D design software.

The software can be easily accessed and used either though a web browser or free software downloaded to local computers that are supported with operating systems like Windows, MarcOS, Linux 32 bits and 64 bits, Raspberry pi.

In July 2016, 3D Slash launched its new app version 2.6.0 with modifications for better user experiences yet the basic toolsets still consist of:

- Hammer: remove one cube at a time
- Trowel: rebuild one cube at a time
- Chisel: remove slices of cubes
- Wood paste: rebuild slices of cubes
- Drill: remove a piece from the model
- Colour options.

Figure 1: *The toolbox in 3D Slash 2.0. (Photo courtesy of all3dp.com) [10].*

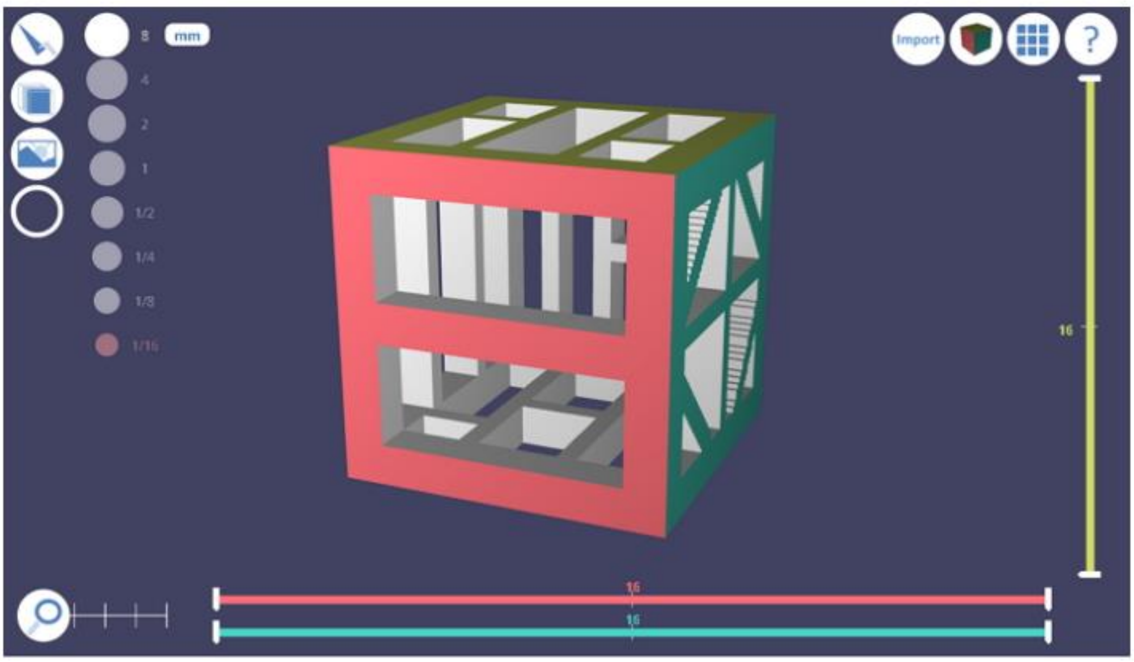


Figure 2: *3D Slash user interface with simple design [11].*

After designing, the model can be saved with the .3dslash extension, users can also export the file as a STL format and also send it to the 3D printer. Also, the software allows users to import existing STL files from elsewhere, customize them with the toolsets and proceed as they please [10]. Recently, 3D Slash has become a feature app in Thingiverse, the biggest printing platform that has a huge amount of designs, which allows all the Thingiverse users to customize STL files (with 3D Slash tools) available in the platform without having to transfer from one program to another [12]. 3D Slash is proprietary software.

2.4 Tinkercad

Tinkercad was initially founded by Kai Backman and Mikko Mononen in 2011. Later, it was acquired by Autodesk in 2013. It self-proclaims as the first browser-based 3D design platform that is introduced to the majorities [13] .

Tinkercad is an option for people with no prior background in 3D modelling. The program is easy to use and the system for designing is fairly similar to 3D Slash, so that available shapes are pieced together or subtracted from each other, contorted or stretched to form a new shape [14]. Moreover, the software is frankly intuitive when no tools such as draw/add, remove/erase are involved, shapes used to build are also tools to modify other existing shapes, adjusting sizes is just as easy as using mouse to pinch the shape's face and drag or retract it.

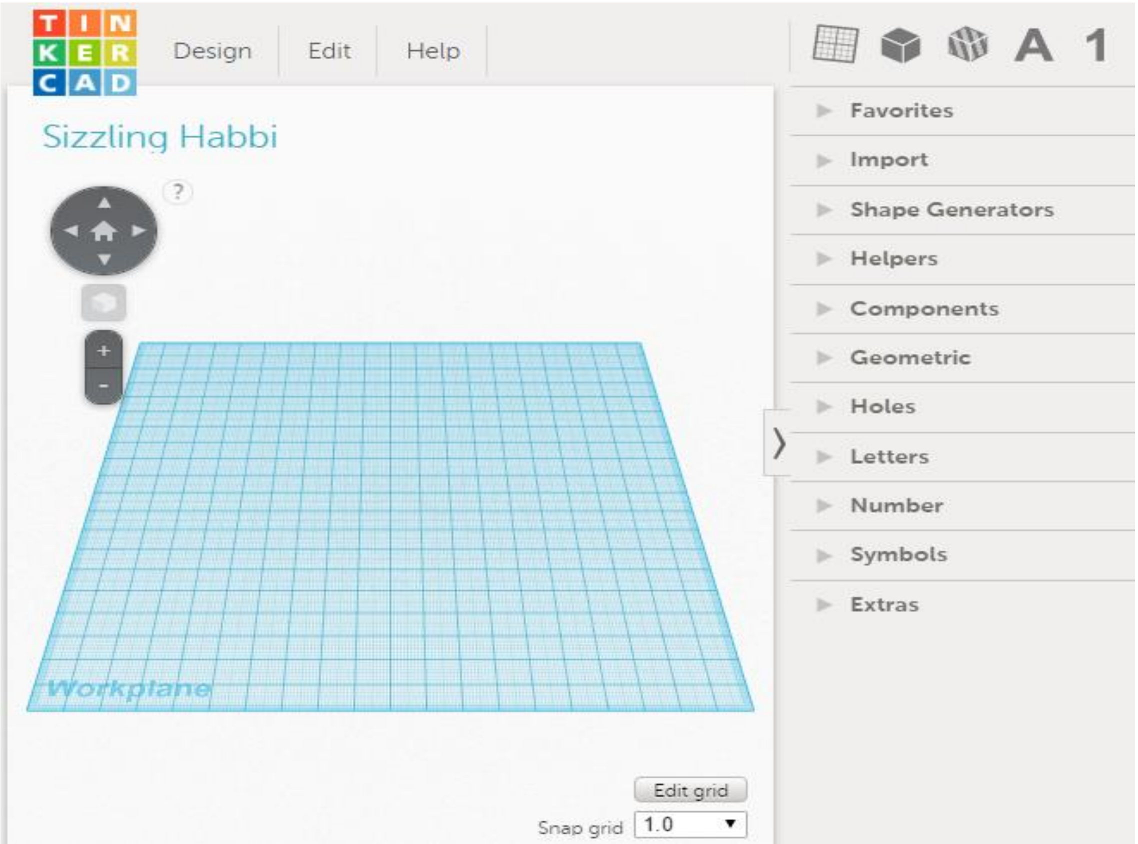


Figure 3: *Tinkercad user interface.*

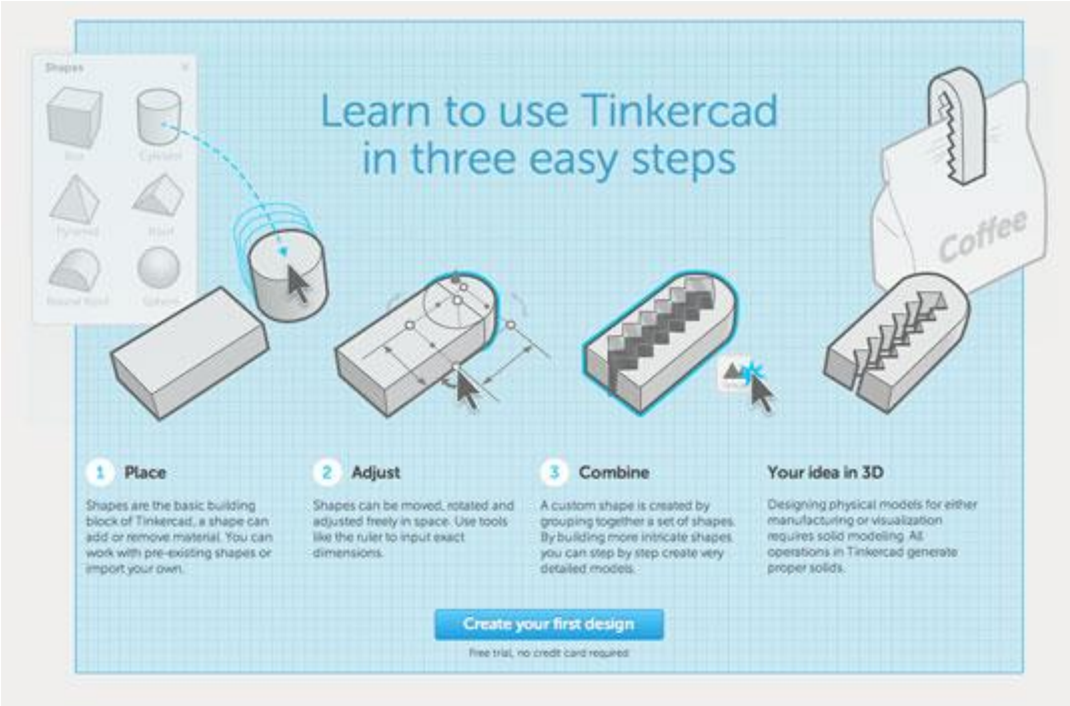


Figure 4: *Schematic of a tutorial video using Tinkercad [15].*

The software homepage also allows a direct link to its gallery of more than four-million designs created by other Tinkercad-ers. A registered user can download to get inspiration or to modify the designs as they want to. To make modelling even more effortless, users who begin to design with Tinkercad are provided with basic interactive lessons to get used to the interface and features.

Tinkercad can run on Mac, Windows and Linux operating systems that enable WebGL, which means only Chrome and Firefox at this time [16]. Although there is a limitation on the browsers to choose from, the web-based operation of Tinkercad makes up for it by storing the models on the cloud, thus users can get access to their models from anywhere, and from any computer.

The software homepage likewise plays role as a 3D platform by allowing users to export models as .stl files and send them directly to their printer, or else, alternatively, Tinkercad collaborate with a third-party service that can print it for the user, making it very self-sufficient [14].

2.5 SketchUp

SketchUp or Google SketchUp as it was called when it was first released, is more of an intermediate level modelling software compared to 3D Slash, since it is tailored for application drawing of architectural, interior design, civil, mechanical engineering and even video games.

Though the targeted application of SketchUp seems to leap a big step from what an intermediate user would actually do, the software is said to be the easiest to use among other available 3D modelling programs. The learning curve of SketchUp is favourable, and users can expect to create something recognizable within few hours [17].

Trimble Navigation, the owner of SketchUp, has also come up with the SketchUp 3D warehouse which is an open source library for users to download, upload, modify and re-upload 3D models. The downloaded models will not take up local computer storage space but will download directly in the software. SketchUp 3D warehouse has made its own, as an extensive learning platform, when allowing models from other software to be uploaded as long as they do not exceed 50 MB. The choice to keep the model private or share it with public is completely ups to the user. It follows that the 3D warehouse assists a wide range of modellers and can totally stand on its own, just in the same way as Thingiverse.

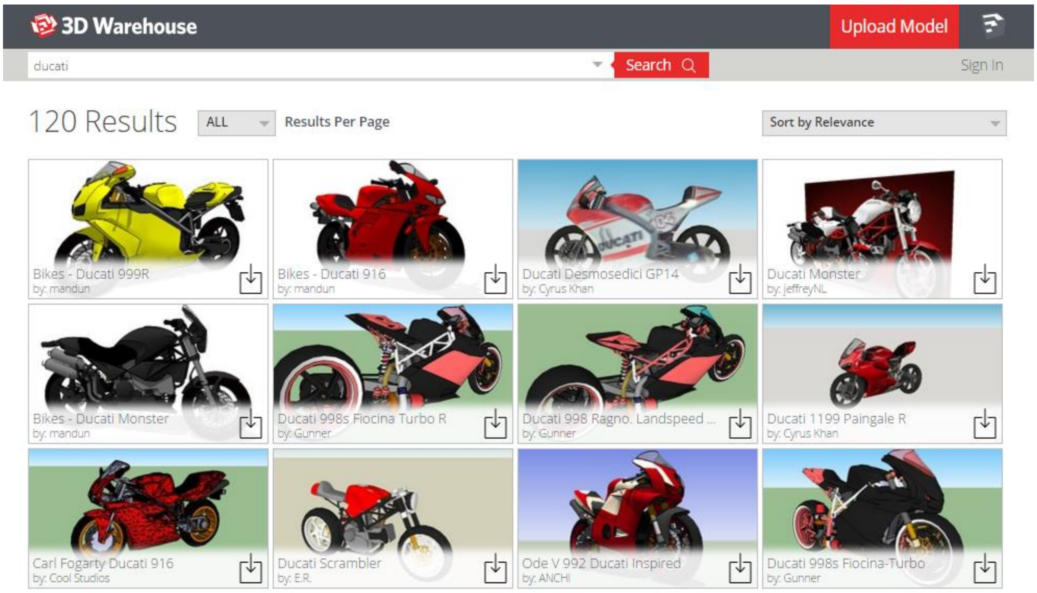


Figure 5: *Screenshot of 3D Warehouse with the word search "ducati" [18].*

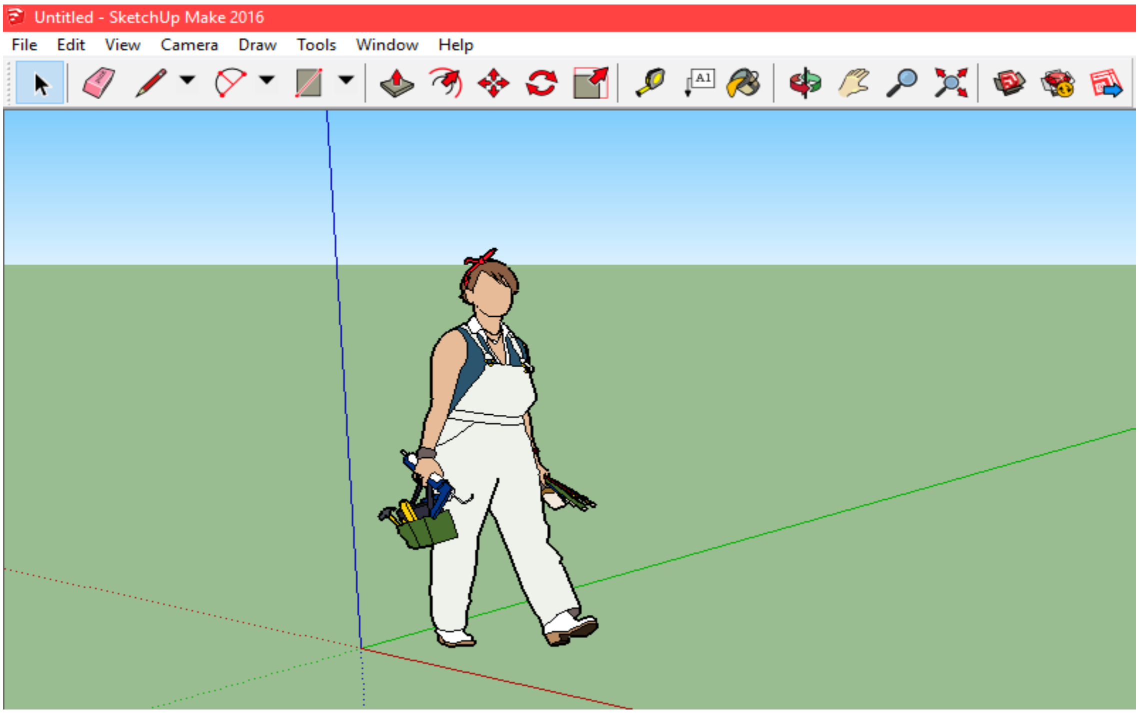


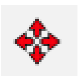
Figure 6: *User interface of Sketch Up 2016.*

The toolbox of SketchUp Make basically covers similar features as other CAD program such as

 Eraser tool: to erase, soften or smooth entities in the model,

 Line tool: to draw straight lines or make free hand-drawings,

 Pull/push tool: to add or subtract volume from 3D model,

 Move tool: to move, stretch or copy entities,

 Paint bucket tool: to assign materials and colours to entities.

Besides the free of charge SketchUp Make, the company also stepped up its modelling game with SketchUp Pro, which offers additional features for professional use. Both versions are proprietary, yet the plugins of both (from version 4 onward) can be modified using Ruby programming language which broadens the way SketchUp benefits its users in a way no other software can [19].

The post-designing process of SketchUp is a quite common function, in which users can save designs as a CAD file or install the “SketchUp STL” extension to save it as a .stl file so that a 3D printer can read it. SketchUp can run on both Mac and Window operating systems with certain hardware requirements.

In October 2016, SketchUp launched the Beta, web browser based version of its software, with the intention of raising accessibility and productivity for their users. Since my.sketchup.com is still in the development state, some features will not be equivalent to its desktop version. MySketchUp can run on Chrome 42+, Firefox 35+ and Safari 8+ web browsers on a desktop or laptop computer. Tablet and smart phones are not recommended to date, as touch gestures are not yet implemented [20].

2.6 Onshape

Currently in the picture, the basic and intermediate level CAD software, which is for enthusiasts and hobbyists all enable both their desktop and web browser version. While the industrial or advanced level CAD software such as SolidWorks and Blender, which are to be reviewed, have their program exclusively ran on the device that has the software installed.

Paradoxically, mechanical CAD designers are usually the ones, who need to have their files mobile. It could be at construction sites, factories and so on.

Understanding the circumstances, the team behind Onshape has released this happy medium that does not only have a bite of each but it also has the innovative approach, which makes Onshape truly a unique CAD software.

Onshape is a parametric[1] mechanical modelling program that is completely operated on the web browsers. The Onshape's set of tools pretty much includes what it needs for solid modelling and surface modelling, the software provide a wide range of the video tutorials that are easy to follow and actually encourage users to do it along [21].

Being aware of itself as a subsequence in the market, beside from their own, Onshape has blatantly let the users decide the view manipulation preference (rotate, constrained rotate, pan and zoom) as if they are using other well-known software such as SolidWorks, AutoCAD, Creo and NX10, in the Onshape workspace. Moreover, once trying out using the software, users can easily recognize that Onshape designing features are strikingly similar to SolidWorks, which more or less sparks up questions about what Onshape has to offer that is different from its mainstream ancestors. The answers reasonably lie in the cloud-based aspects:

- The software automatically saves changes all the time, so the user can trace back and undo every step of the designing process.
- Update is done frequently and automatically by the system itself.

[1] "Parametric is a term used to describe a dimension's ability to change the shape of the model geometry as soon as the dimension value is modified" [48]

- Enable touch gesture so that users design on their tablets, or even phone. As the progress is completely done in the cloud base, it will not take space on the device (computer, tablet or phone) and does not require any strong processing power or graphic cards.
- Allow team members from anywhere to work on the same file, at the same time, with the record keeps track of what has been changed to the file and by whom. This shortens the time the product is introduced to the public from days and months to minutes and hours, and at the same time boosting innovation as it is a parallel, collaborative process.

Beside the educational version, Onshape offers the free version having complete functionality, which is rare for a mechanical CAD software, with up to 10 private design files within 10MB and unlimited public files, all saved in the cloud [21].

Thanks to the “Agile Product Design” motto and addressing the real world problems, Onshape has won over many users and nailed a huge funding from $9 million (2012) up to $169 million (2017) [22]. It’s an impressive growth that which can be concluded as “the company’s progress to date has been a rollercoaster to watch” [23].

2.7 Blender

Out of all the freeware mentioned, Blender is the most powerful freeform modelling tool both in modelling competence and vast graphic application areas. According to Blender.org, the open source software "supports the entirety of the 3D pipeline modelling, rigging, animation, simulation, rendering, compositing and motion tracking, even video editing and game creation" [24]. As a result, Blender's learning curve is very steep and is often not recommended for beginners, that is unless one has mastered basic modelling steps and crave sophistication for one's 3D printing model, Blender is the way to go.

In 1995, when it was first launched, Blender was a proprietary software. That is until 2002, when a campaign calling for the source-code had made the required payment of 100 000 euro during seven weeks, so finally the software and its source-code are now free to the community [25].

Since then, the public has been entitled to make considerable changes to the source-code, which "lead to new features, responsive bug fixes and better usability" [24] . Consequently, Blender has released 36 versions one after another over the last 14 years (from 2002 to September 2016) keeping itself constantly innovative, directly meeting the needs of the users as they are the ones using and submitting their re-coding for creating a better version.

In contrast, the freedom of Blender's usage is a double-edge sword as other companies tried to exploit the open-source nature to re-brand and cosmetically-modified Blender as their own. Some names can be mentioned as Blender-based software such as IllusionMage, Fluid Designer or 3DMofun [26].

Blender can be installed and run equally well on Mac, Windows or Linux computers, and the latest version released up until now was on September 30, 2016 and is Blender 2.78. Blender supports many different programs with a large range of extensions for image, video and 3D printing such as 3D Printing Toolbox; a sufficient tool to prepare models before printing.

Not only the level of design has surpassed other freeware, Blender is also equipped with a rendering tool, material assignation, cloth simulation and fluid simulation.

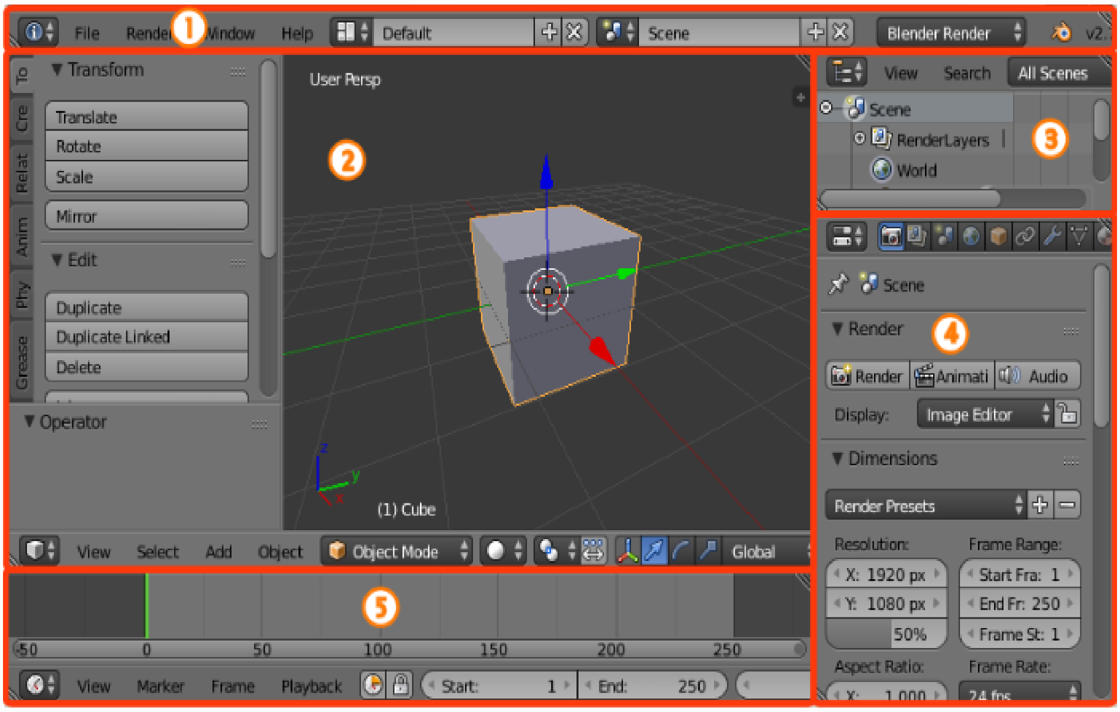


Figure 7: *Blender screen layout (version 2.77)*
Info(1), 3D View(2), Outline(3), Properties(4) and Timeline(5) [27].

Though new users may find it daunting to start with a new complex software, Blender actually has the biggest learning and 3D printing community, which keenly practices their open-source spirit by sharing and spreading resources. A survey made in 2015 by a member of the company i.materialise based on four factors of:

- 3D printing forum mentions
- 3D printing video
- 3D printing databases
- 3D printing Google score, to find out the Top 25Most popular 3D modelling software for 3D printing and Blender, by average score won the first place [28]

Table 1: *Screenshot of top 10 from 25 most popular 3D modelling software for 3D [28].*

Top 25

Most Popular 3D Modeling Software for 3D Printing

		General		3D Printing Community				Total
		Social	Website	Forums	YouTube	Databases	Google	Score
1	Blender	61	91	100	100	27	100	**80**
2	SketchUP	87	82	79	49	80	74	**75**
3	SolidWorks	95	81	42	52	25	75	**62**
4	AutoCAD	100	78	46	43	4	85	**59**
5	Maya	91	80	35	50	3	93	**59**
6	3DS Max	90	83	24	53	2	78	**55**
7	Inventor	98	80	29	31	15	75	**55**
8	Tinkercad	78	57	38	5	100	31	**51**
9	ZBrush	83	69	45	42	4	50	**49**
10	Cinema 4D	84	76	6	28	1	62	**43**

2.8 SolidWorks

SolidWorks Corporation is a Massachusetts based company originally founded by Jon Hirschtick in December 1993. At that time, Jon and his team were aiming towards creating a CAD software that runs on Microsoft Windows, easy to access, to use and affordable. Following this intention, two years later the first ever SolidWorks 95 was released, within the first two months, the software had successfully proven all of its claims, encouraging engineers to make use of CAD software in product designing.

In 1997, Dassault Systèmes, a global lifecycle technology company, which is famous for its CATIA CAD, acquired SolidWorks for $310 million in stock.

During 20 years of operating (1995-2016), DS SolidWorks has continually been innovating its toolsets and now over 25 versions of SolidWorks has been released, and the company has stated that they have more than three million users over 80 countries in the world and "knowledge and understanding of SolidWorks" has become the most prioritized sought after requirement that employers value when head-hunting candidates in the 3D technology field, in Monster.com page, which is one of the most powerful employment websites. [29]

SolidWorks users range from individuals to corporations, as it covers a wide cross-section of manufacturing, industrial, medical, scientific, educational, technology and transportation.

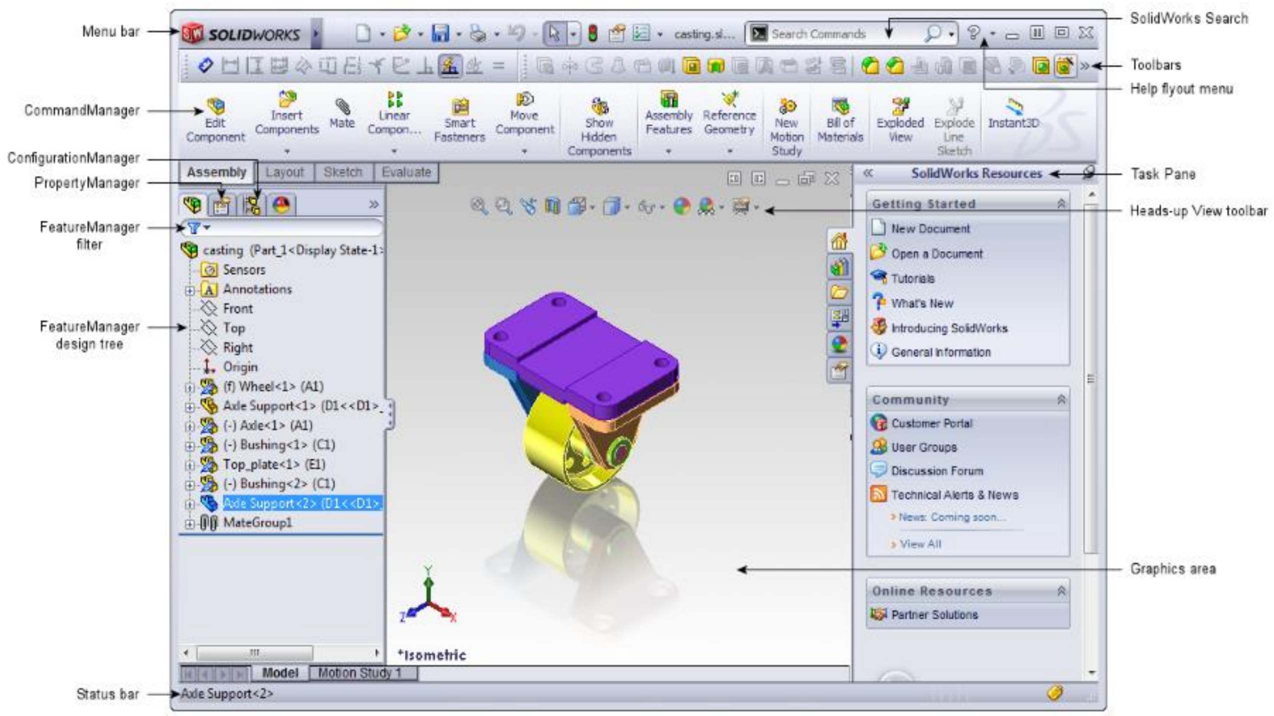


Figure 8: *SolidWorks user interface [30].*

Since SolidWorks is a proprietary software that costs thousands for a license (starting from US$4000 and may reach to US$10000 with add-ons and subscriptions) [31], training is essential to make it a worthwhile investment, even with the educational version, which students can get free of charge. There is definitely a continual learning process involved going through tutorials to get the hang of the program. Additionally, commercial sale is made through an indirect channel and as the enormous value of the licensed package, it is not easy to know everything that SolidWorks has to offer unless one has access to it oneself.

The dynamic capabilities of SolidWorks provides diversity in multi-industrial libraries, product lifecycle management (PLM) or product data management (PDM) which is probably redundant for individuals or 3D printing-enthusiasts [32]. These are admirable qualities in industry but of little use to the hands-on designer. Just as some programs are inadequate as far as designing is concerned, SolidWorks is too overloaded with potential that cannot be usefully employed by designers.

One minus point for SolidWorks is that it does not naturally work on Macintosh computers since the software was initially tailored to run on Windows. However, since Apple Inc. now uses Intel chips for their computers, users can install Windows and run SolidWorks on Mac computers [33].

2.9 MakerBot Printer and printing material

MakerBot is an American company providing desktop 3D printers, found by Bre Pettis in 2009 and later acquired by Stratasys in 2013. MakerBot was one of the pioneers in “making 3D printing accessible and affordable”. Until April 2016, MakerBot became the first company in the industry to sell over 100 000 printers worldwide, and the number is still increasing. Moreover, MakerBot also found and ran Thingiverse - the first and biggest online printing platform and file repository [34].

The printer that was used for realizing the two models was the MakerBot Replicator + 5^{th} Generation printer, material was PLA, provided at the Arcada premises. MakerBot Replicator + 5^{th} Generation was released in January 2014 together with Replicator Mini +, Digitizer desktop 3D Scanner and is the latest until now.

The printing mechanism is Fused Deposition Modelling (FDM), which is the most common 3D printing method. Thermoplastic filament is fed through a heated head, the extrusion nozzle then deposits the molten plastic in X and Y direction while the print bed moves down (or the extruder moves up with other types of printers) in Z direction to create the model layer by layer [35].

This FDM technique of printing is best for product development, rapid prototyping in small businesses and education, as it is adequate for building models quickly and cost-effectively.

There is a wide range of choice for materials used in FDM, most materials used are strong and sturdy, which makes FDM printed products suitable for “functional testing, as well as form/fit testing” [36] .

Nonetheless, the nature of the printing mechanism produces printing lines, which can be seen on the models, the supports will leave marks, and the small details would not be as precise as using the earlier mentioned SLA or SLS. Hence, post-printing processes such as polishing or finishing would be needed, adding up the time for the completed models [36].

At the moment, PLA and ABS are two dominant materials that are used in FDM; however, the list of printing material should not be limited, but rather expanded to meet the specific needs of a given printing object. The following table displays six pure polymers that exist in the market nowadays and their applicability for 3D printing over seven different criteria [37].

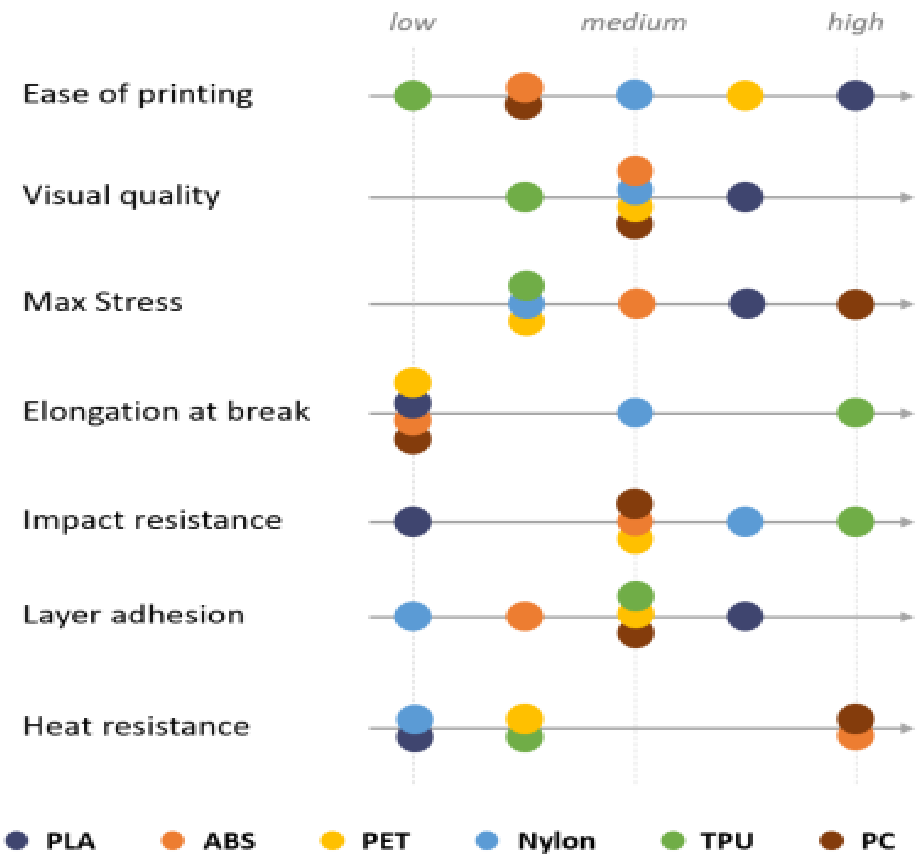


Figure 9: *Research results for six polymers used in FDM [37].*

Besides manufacturing 3D printers, MakerBot produces their own filaments for their 3D printers, which are specifically optimized for the slicing algorithm with their dedicated slicer, to help customers achieve the topmost printing results with MakerBot 3D Printers.

There are four kinds of MakerBot filaments that have been designed for different purposes, on the market at the moment:

- MakerBot PLA filament: non-toxic, safe to be used in open environments. It comes in natural colours, opaque, translucent and luminous.
- MakerBot ABS filament: its physical attributes make it suitable for engineering and testing, offers greater impact resistance than PLA. ABS comes in opaque colours.
- MakerBot dissolvable filament: it provides supports for delicate, complex design when printing with ABS. It is normally used with dual extruders MakerBot Replicator 2X Experimental 3D Printers. The filament comes in one colour and dissolves in limonene, a citrus-scented solvent.
- MakerBot Tough PLA: this newest filament has been enhanced to be suitable to print high-impact and all round strength prototypes and various engineering items that need durability. This filament requires the Tough PLA Smart Extruder + for best results. [38]

2.10 Analysis using SWOT and multi-criteria decision making using AHP

SWOT is an analytical method that is widely used to identify and organize internal elements of business ventures, organizations, products or personnel and is based on four factors:

- Strength and Weakness (internal factors)

- Opportunity and Threat (external factors).

SWOT covers hard facts of objects under analysis. Prioritizing and order of listing does not reflect the significances of the factors that are mentioned. The method is favoured by many, due to its simplicity and flexibility. [39]

The application of SWOT can reach to, but in no way is limited by profit-seeking organizations. It can be used in situations that require decision-making when the objectives are clear and when "creating a recommendation during a viability study/survey" [40]. The following schematic example of SWOT analysis is shown with assisting questions for the users to answer while building up the analysis.

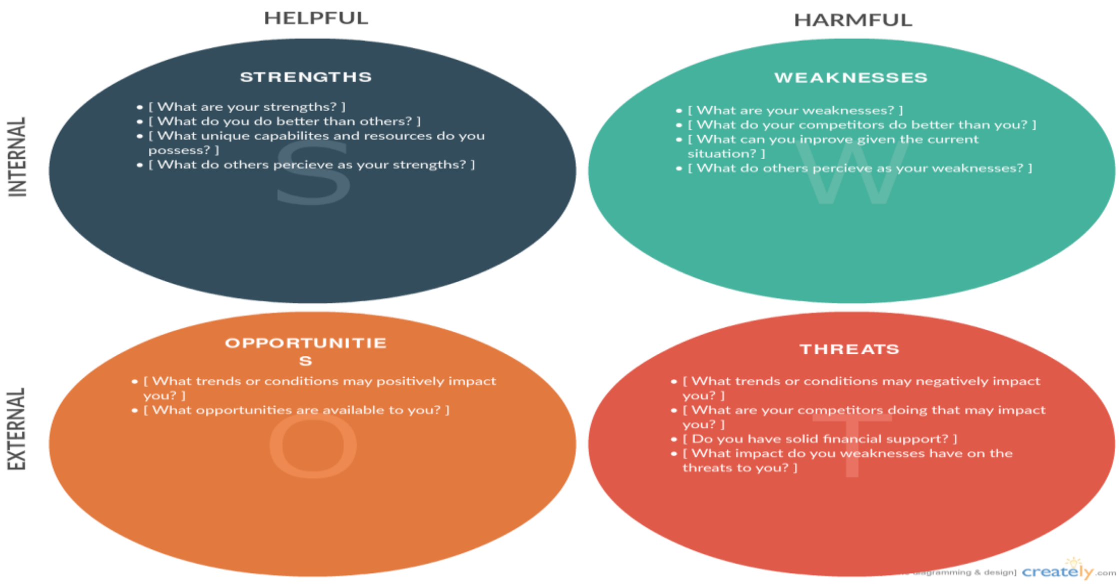


Figure 10: *Example of SWOT analysis [41].*

Along with SWOT, another decision-making method Analytic Hierarchy Process (AHP) is employed in this thesis work in order to deliver a goal-oriented result out of the two software products being compared, based on the pre-determined objectives.

Analytic Hierarchy Process bases its fundamental analysis on mathematics and psychology. This method helps decision-makers to map out a rational and complete framework of decision problems. By subdividing the problem into a hierarchy, each element of the hierarchy is analysed independently. The elements of the goal are the sub-criteria; each sub-criterion is given a numerical evaluation to identify which is the more significant among them. "In the end, there is a clear decision whose development can be seen, traced, and understood by all concerned". [42]. The mathematical aspect of the process can be helped by using AHP software which is provided online.

For a better understanding of this method, an example of AHP is built up as follows. The goal shown here is to choose one leader for the company among the three candidates.

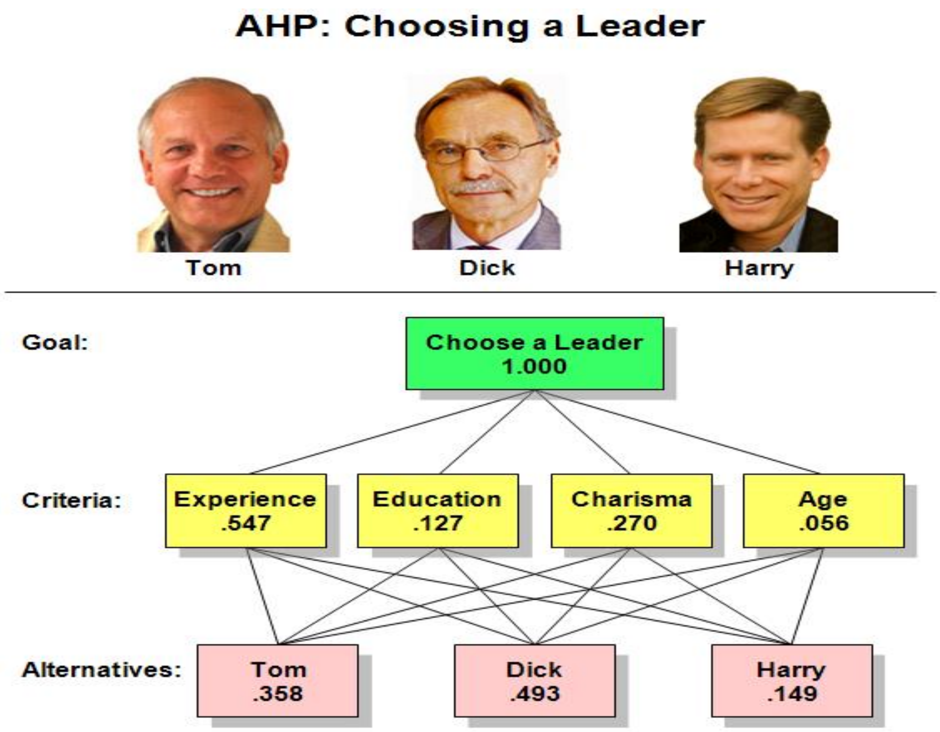


Figure 11: *Example of Analytic Hierarchy Process analysing method [43].*

The motto and goal of the company prevails the leader's experience by more than half of all the all criteria combined. This followed by the criteria Charisma. Education is evaluated roughly less than half of Charisma, and Age comes as the least influence of all criteria.

By analysing a goal with AHP we can see that by sub-dividing the goal into logical criteria and again sub-dividing as necessary, a clear picture of what is required to under-stand the elements that constitute the goal emerges. These elements or criteria can be evaluated individually and these evaluations combined to assess their significance and identify the true goal.

3 METHOD

The object decided upon to be designed in the thesis is a business-card holder.

The card holder is made of a honeycomb rectangle sheet that was firstly inspired by the Voronoi diagram, which can be simply conceived as partitioning a plane based on a set of points on the plane. Voronoi diagram has its application mostly in science (mathematical analyses) and technology, but also involving visual art (pattern in furniture and wall-paper) [44].

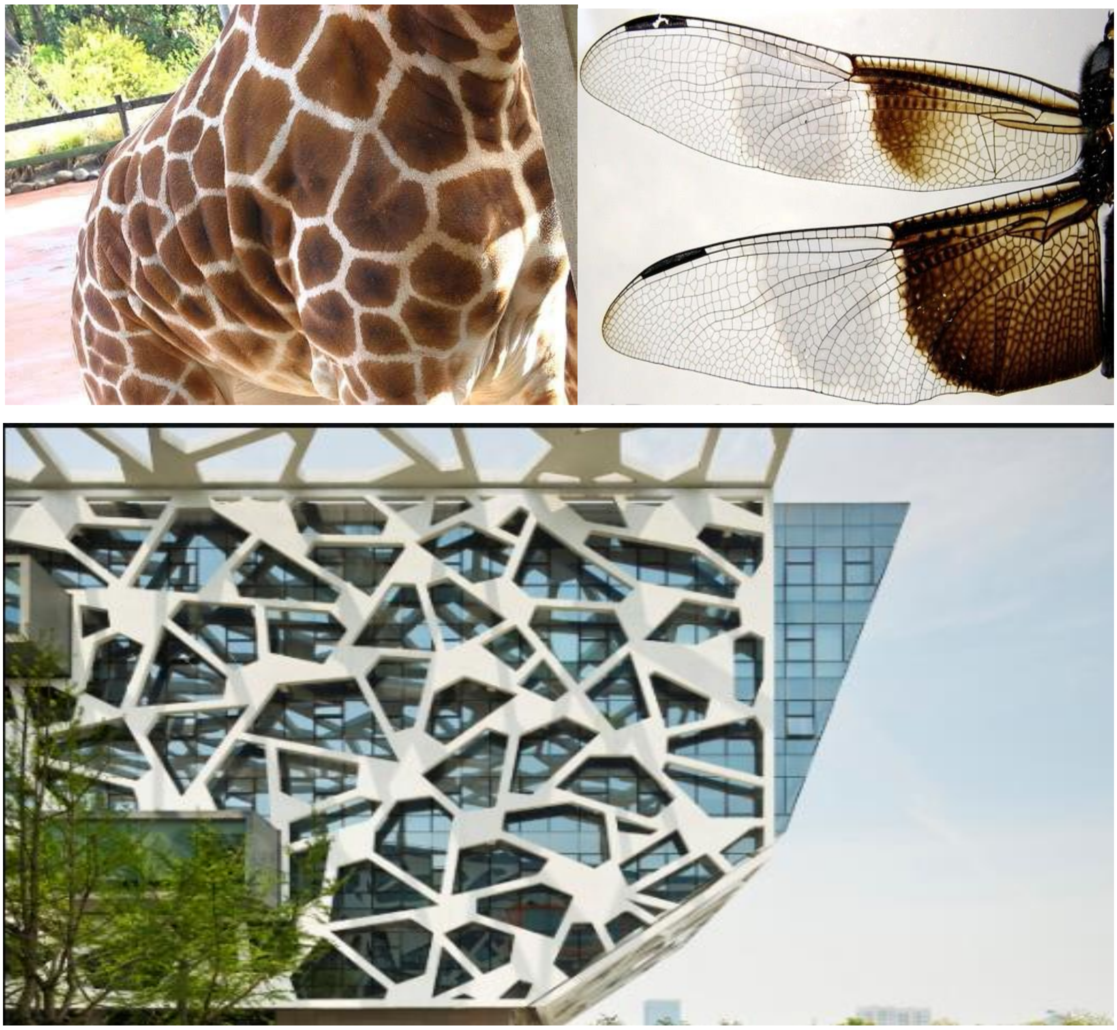


Figure 12: *Voronoi diagram in nature (top row) and in architecture (bottom row) [44].*

European card dimensions are used here 85 mm x 55 mm.

3.1 Design using Blender

Blender version 2.77, released in April 2016. Download from Blender.com

To use Blender:

- Open the Blender screen (there is always a default cube in the centre).
- Left click on the cube to select it and press “x” on the keyboard to delete it.
- Add a cylinder mesh (one of Blender’s primitive shapes) On the blank canvas, by pressing “shift A” or clicking on the “Create” tab at the top left corner of the screen. (The units here can be ignored as the model can be scaled down to a real dimension after finishing the design).

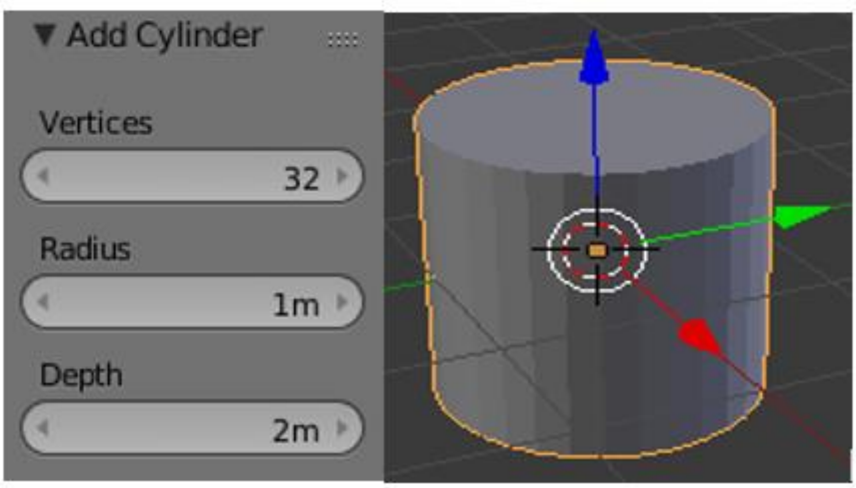


Figure 13: *The cylinder (right) and its information (left).*

To create the honeycomb (hexagon) from this cylinder:

- Change the vertices input from 32 to 6.
- Delete the surrounding faces and one face at the top, which gives one honeycomb surface.

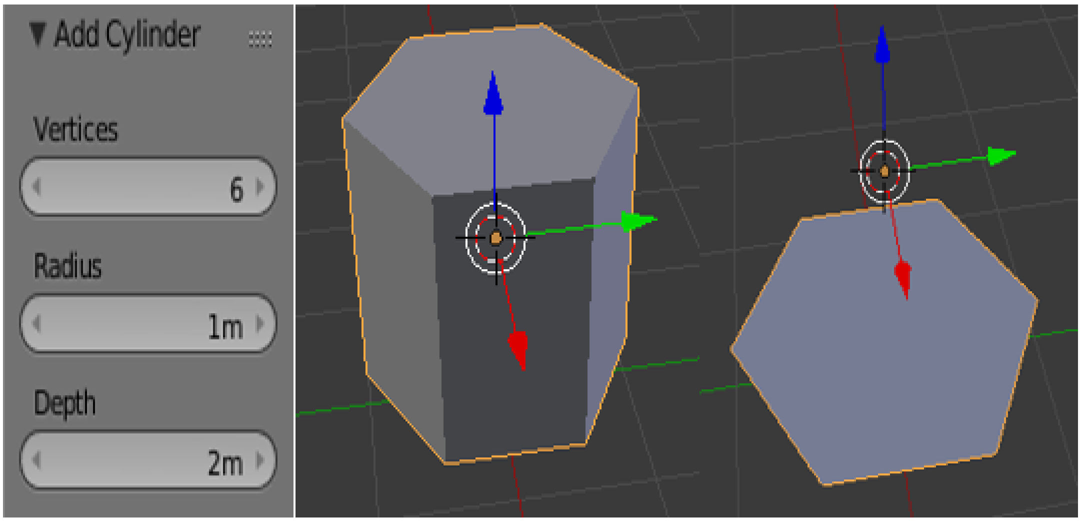


Figure 14: *Steps taken to create a single honeycomb.*

- Pressing the “I” on the honeycomb face to insert a similar face.
- Scale it to be smaller than the original (80%)
- Delete that face to create a honeycomb frame.

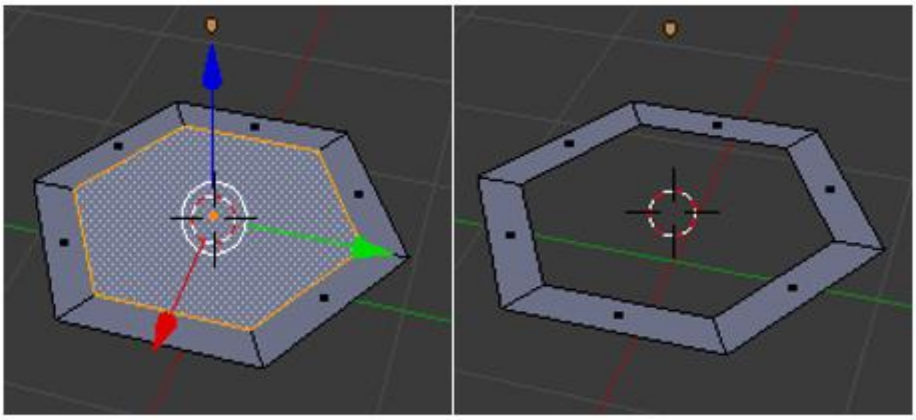


Figure 15: *Honeycomb face inserted (left) and its outer frame (right).*

- Choose “Array” in the modifier drop-down at the right lower corner to duplicate the honeycomb frame.

The inputs are as shown in the following screenshot:

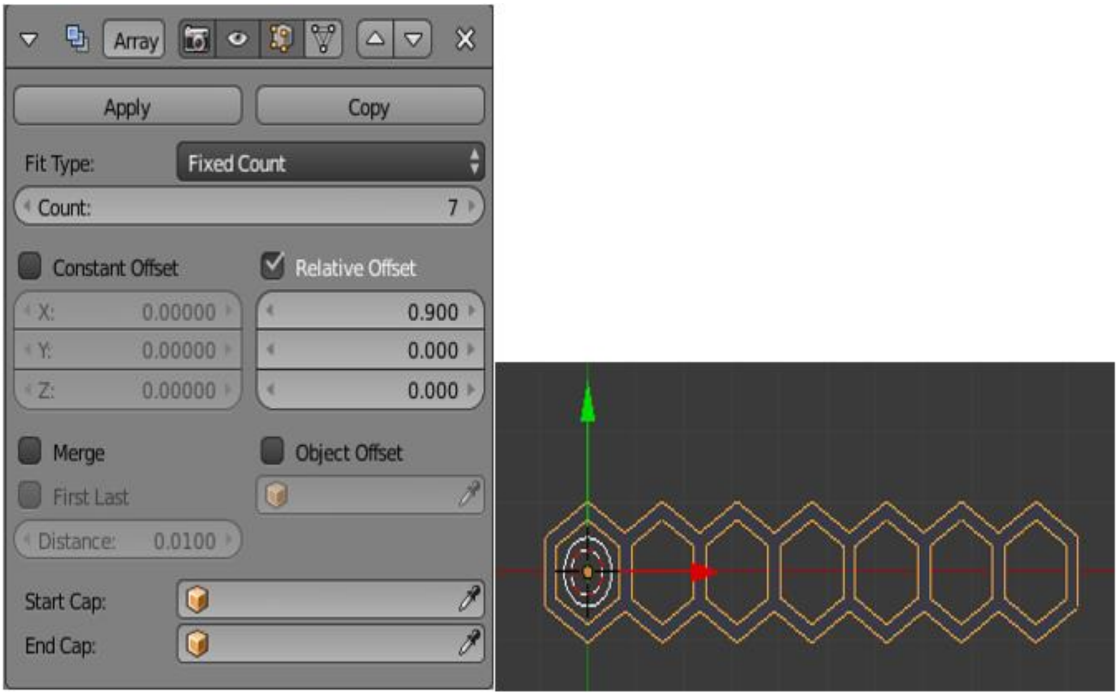


Figure 16*: Array modifier in the X-axis from a single honeycomb.*

- Use the "Array" modifier again, to duplicate the row of the honeycomb in the Y-axis direction. This will achieve a mesh made of honeycomb.

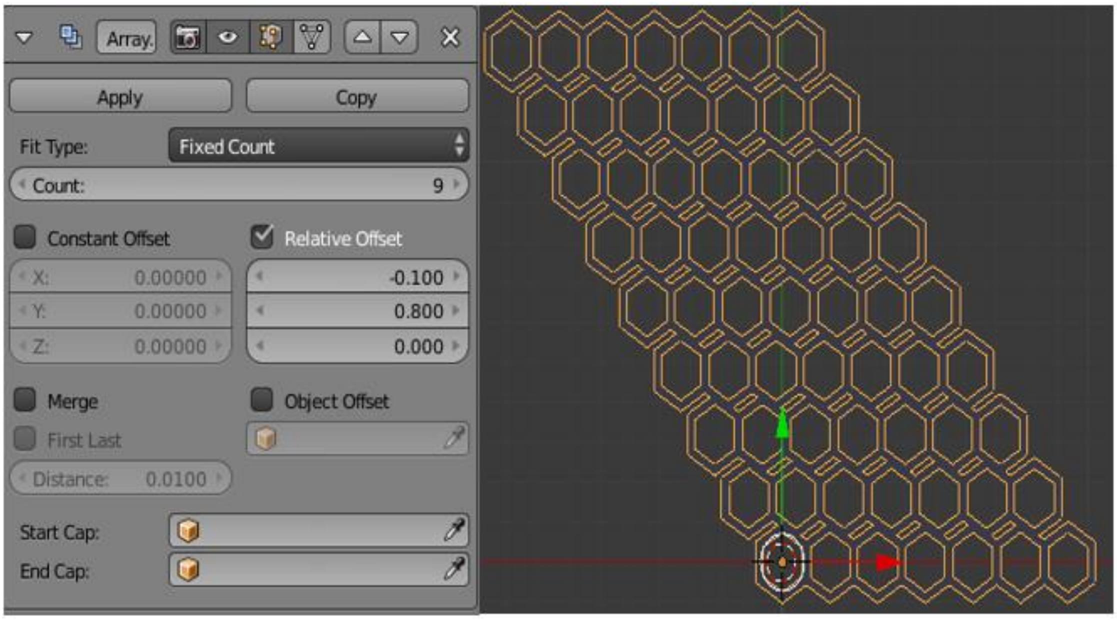


Figure 17: *Array modifier in X and Y direction from a honeycomb row.*

- Add a “Bezier curve” in the same plane of the mesh.
- Restrict the curve to be 2D on the plane.
- Uncheck the Radius box and, check in the Bound Clamp and Stretch boxes.
- Choose both in the Fill drop down.

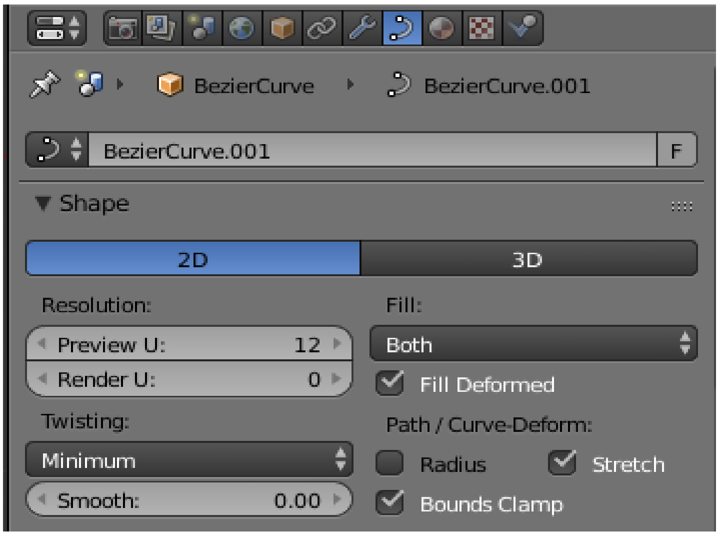


Figure 18: *Bezier Curve parameter.*

- Edit each end of the curve so that it takes the shape of a C. It does not have to be a perfect C as the shape can be altered later.

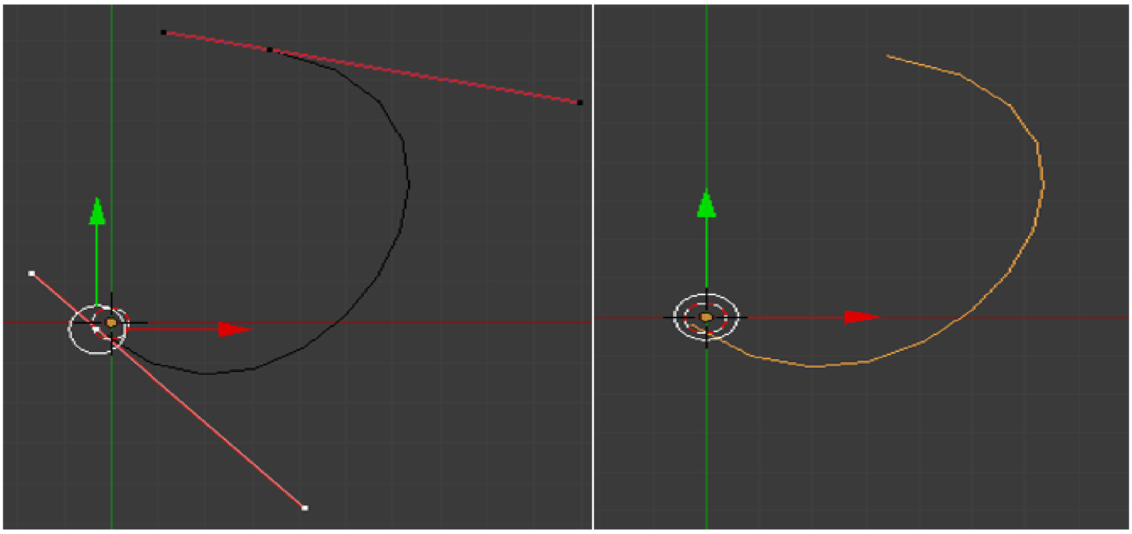


Figure 19: *Bezier curve in Edit mode (left) and Object mode (right), top view.*

- Click on the honeycomb mesh to choose, from the Modifier panel again.
- Choose the “Curve” modifier.
- Choose the BezierCurve as the object, then the mesh will take the shape of the curve, in Y-direction.

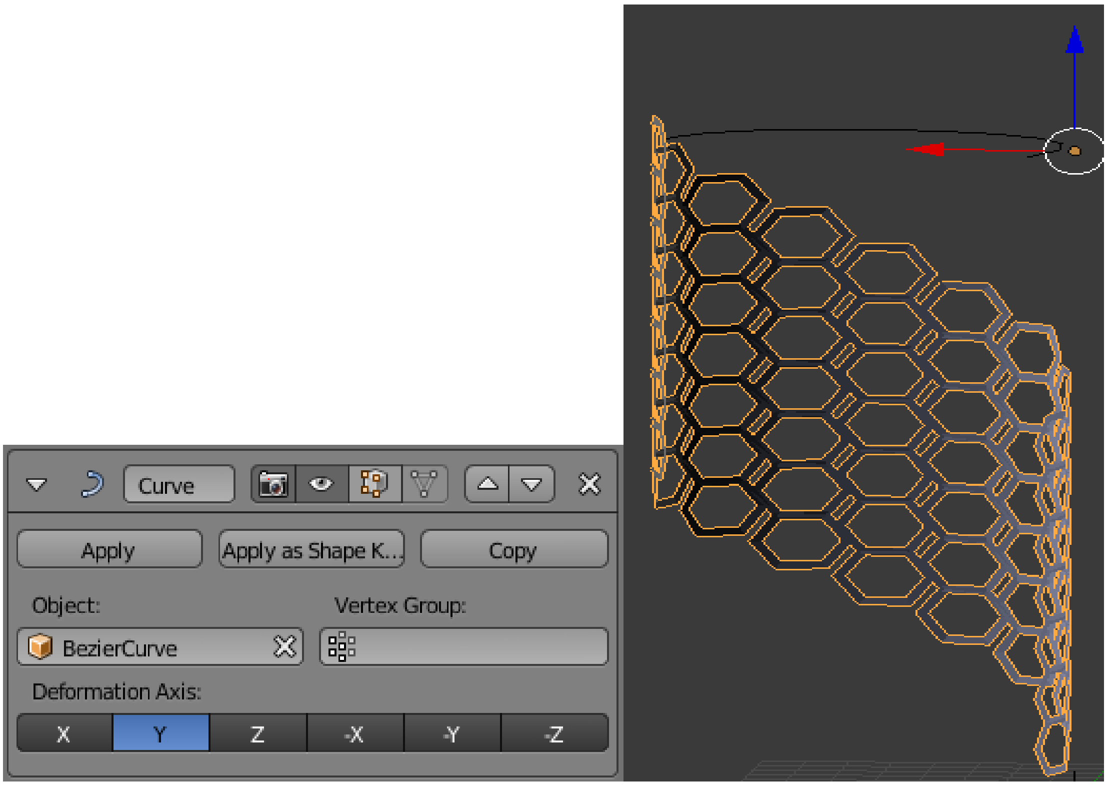


Figure 20: *Curve modifier setting (left) and its effect on the mesh (right).*

- Add thickness (15 cm) to the mesh, after achieving the desired shape, by using the "Solidify" option found in the same panel.

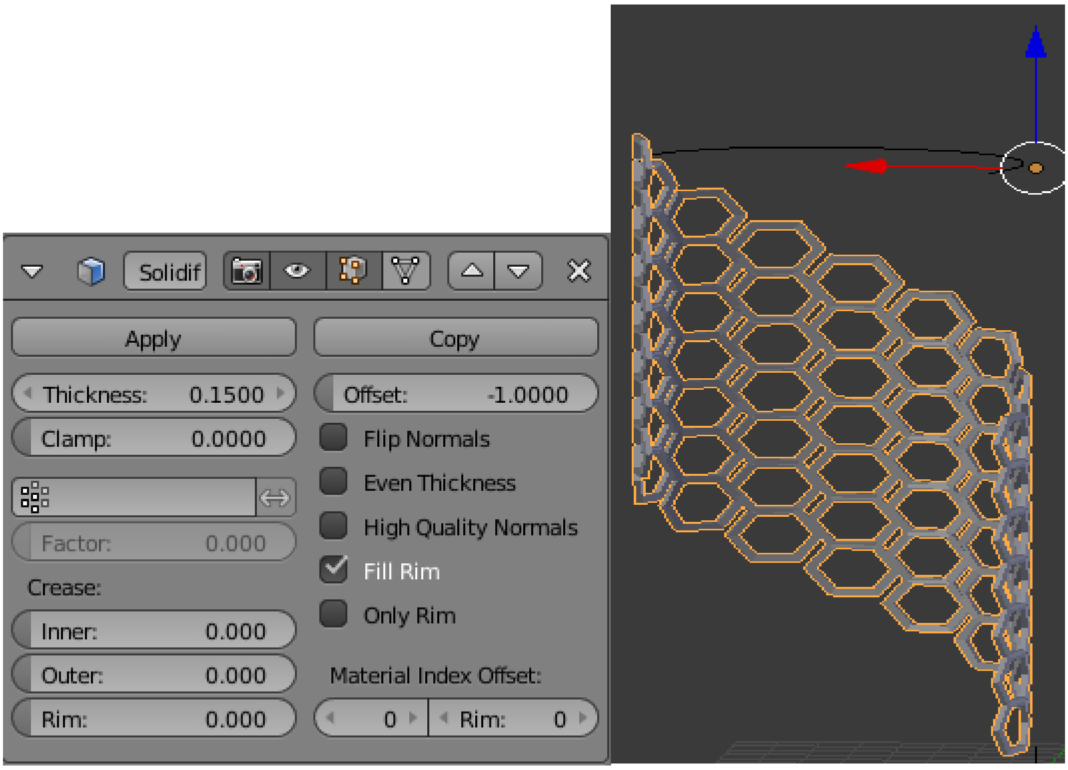


Figure 21: *Solidify modifier (left) and the completed mesh (right).*

Until this step, there were four modifiers used; however, do not click on "Apply" unless you want to make the change permanent. Once the modifier is applied, only to a certain number of steps can be undone, and no change can be made after the modifiers are applied and the program is closed [45].

The mesh was then rotated 90 degrees to lie horizontally, a rectangle block that has dimension of the business card stack was added to place inside the mesh. The Bezier curve now may have to be edited so that the mesh can fit the block's corners. From then on, a base and a corner were add to the mesh.

The final product after rendering shown as follow:

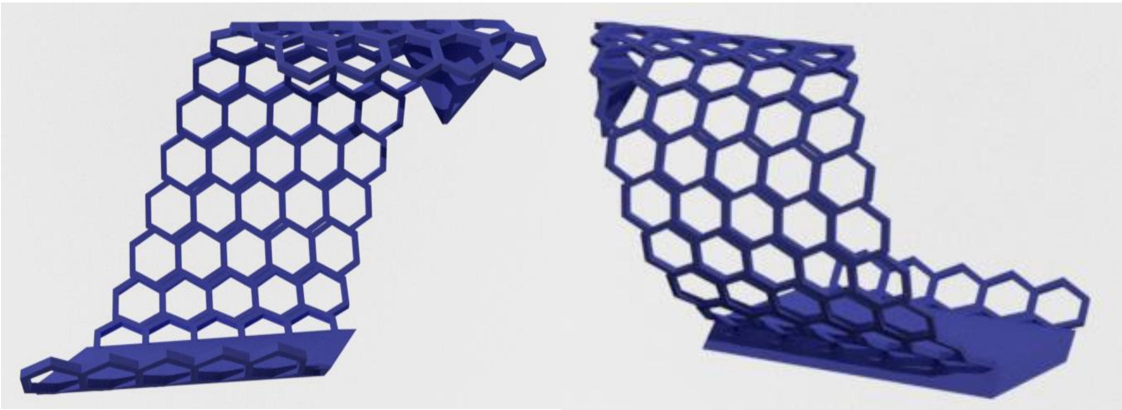


Figure 22: *Business card holder designed using Blender.*
Front view (left) and back view (right).

3.2 Design using SolidWorks

SolidWorks student version 2017, free of charge for students of schools that are qualified for network of SolidWorks licenses. The student version will expire after one year of activation [46].

Designing steps are listed below:

- Create a helix of diameter 61mm (pitch: 5cm, 1 revolution) to resemble the twisting path of the card holder in the right plane.
- Attach one single honeycomb (side dimension of 1 cm and 0.15cm in thickness) at one end of the helix (The honeycomb was on a plane that created a 35 degree angle with the horizontal plane).

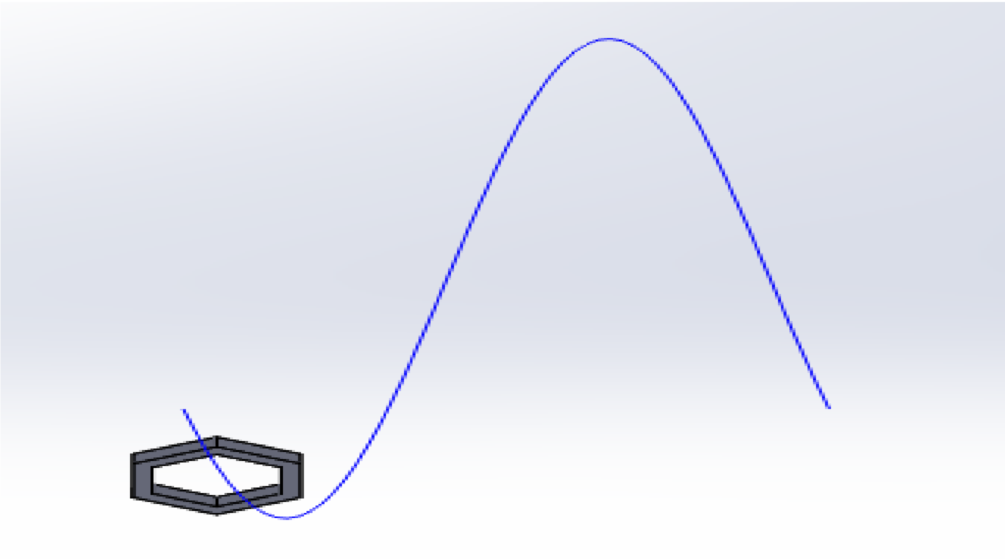
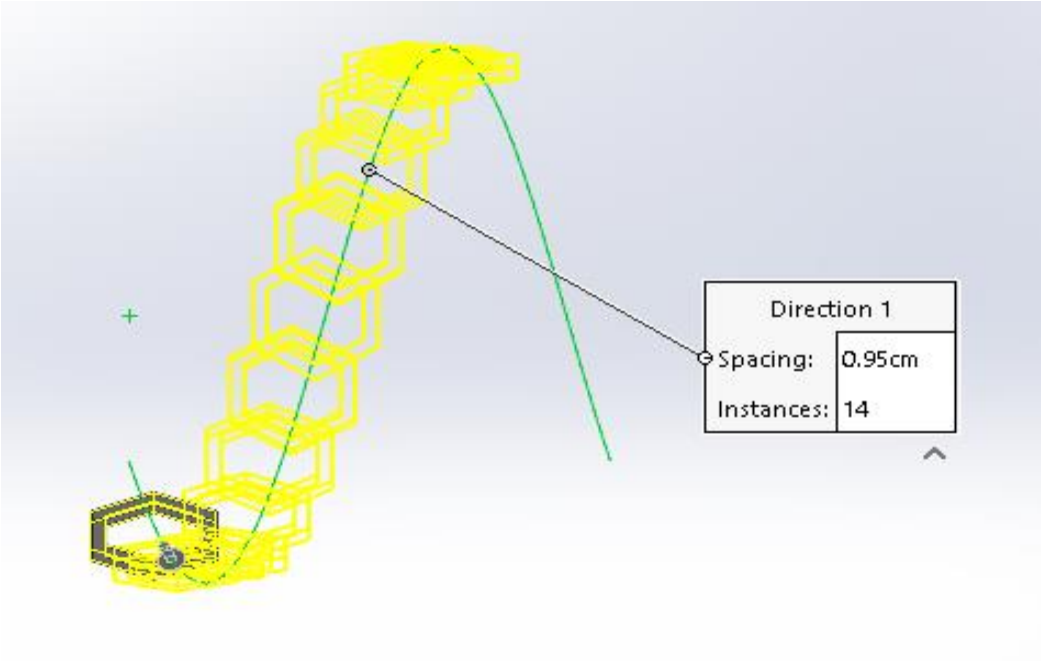


Figure 23: *Helix and the first single honeycomb.*

- Duplicate the honeycomb along the helix and the horizontal line, using "Curve Driven Pattern" feature and followed by Linear Pattern feature.



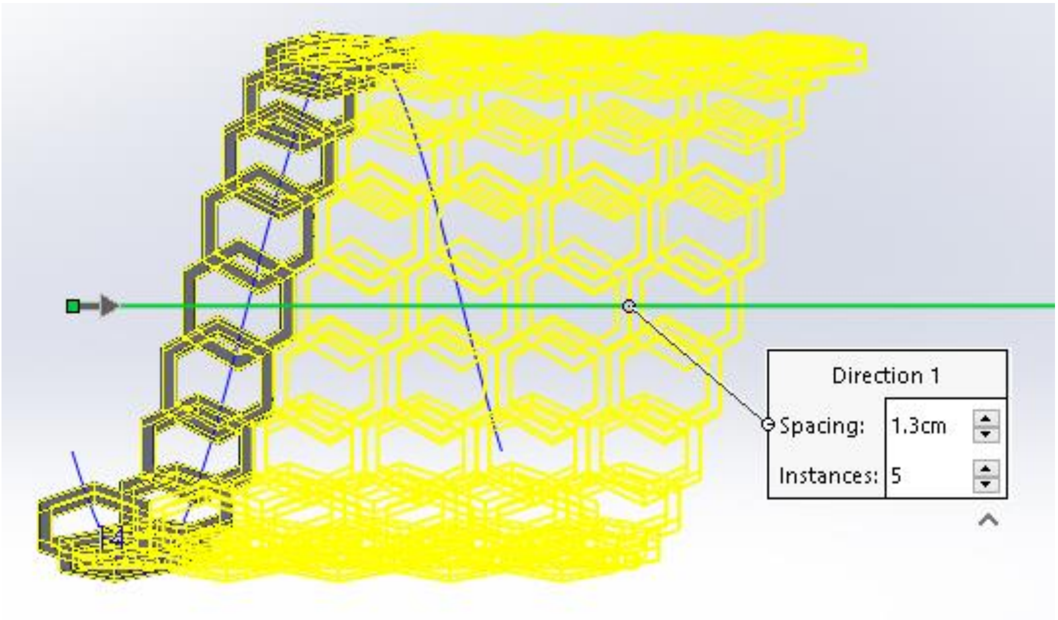


Figure 24: *Curve Driven (up) and Linear Pattern (down) features.*

- Add a base (80 x 20 x 5 mm) in for the honeycomb to stand as in the picture without falling flat on its curving face (belly).
- Add a corner at one end on the top of the honeycomb mesh to prevent the cards from sliding out of their holder.

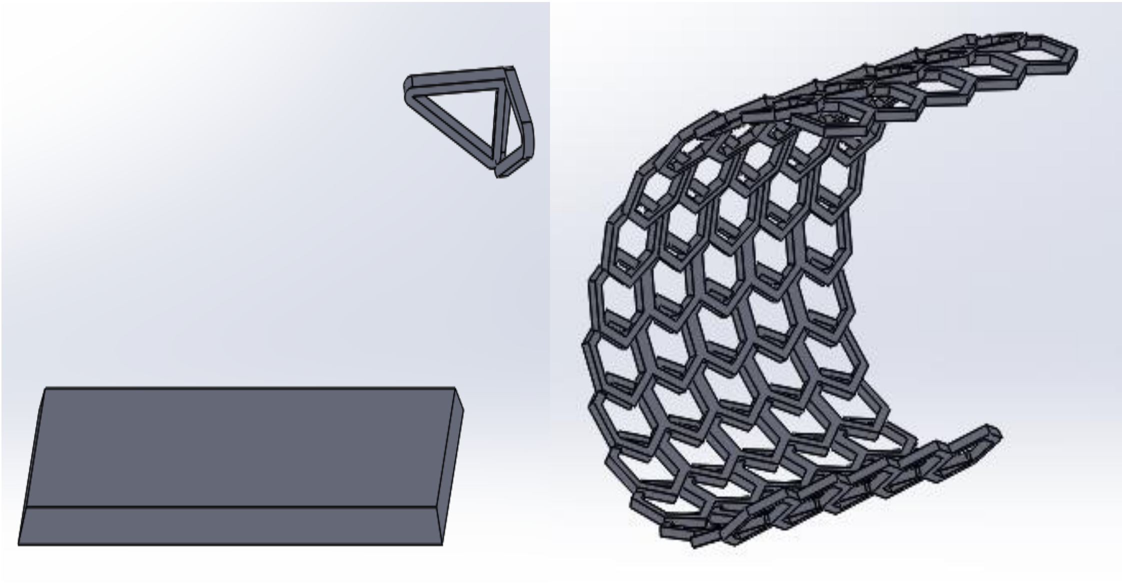


Figure 25: *Left: Standing base and corner, Right: Completed honeycomb mesh.*

The final product was visualized as in the following figure, with the yellow block acting as a stack of cards.

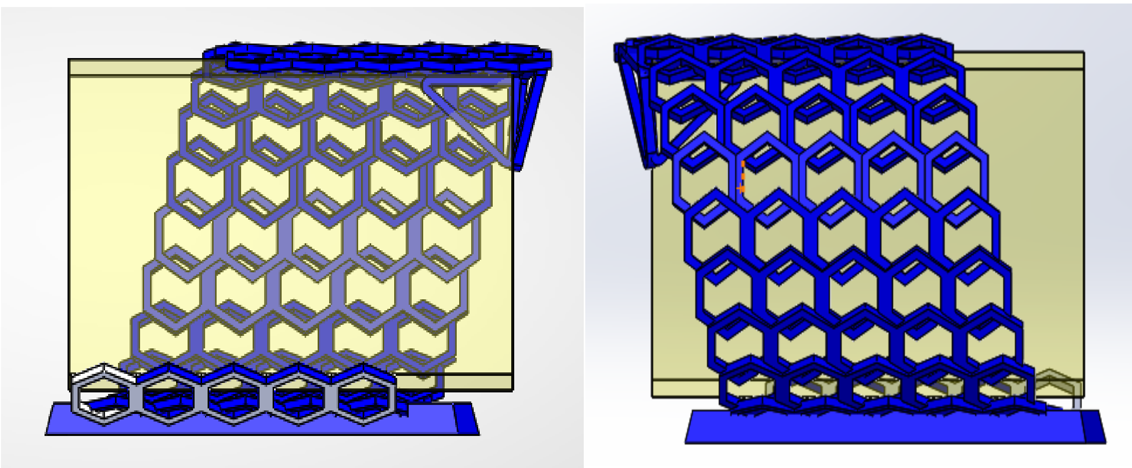


Figure 26: *Business card holder designed using SolidWorks.*
Front view (left) and back view (right).

3.3 Prototyping products

To create a successful model, both of these printed products have had to be laid flat with the vertical section of the curve on its back, as shown in the following figure. In addition, due to the construction of this specific design, a raft and support were added for stability and good adhesion. The printing time was 2 hours 57 minutes for Blender design and 3 hours 24 minutes for SolidWorks design respectively. However, if the two models were to be printed together on the same bed at the same time, then the total printing time is 5 hour 8 minutes.

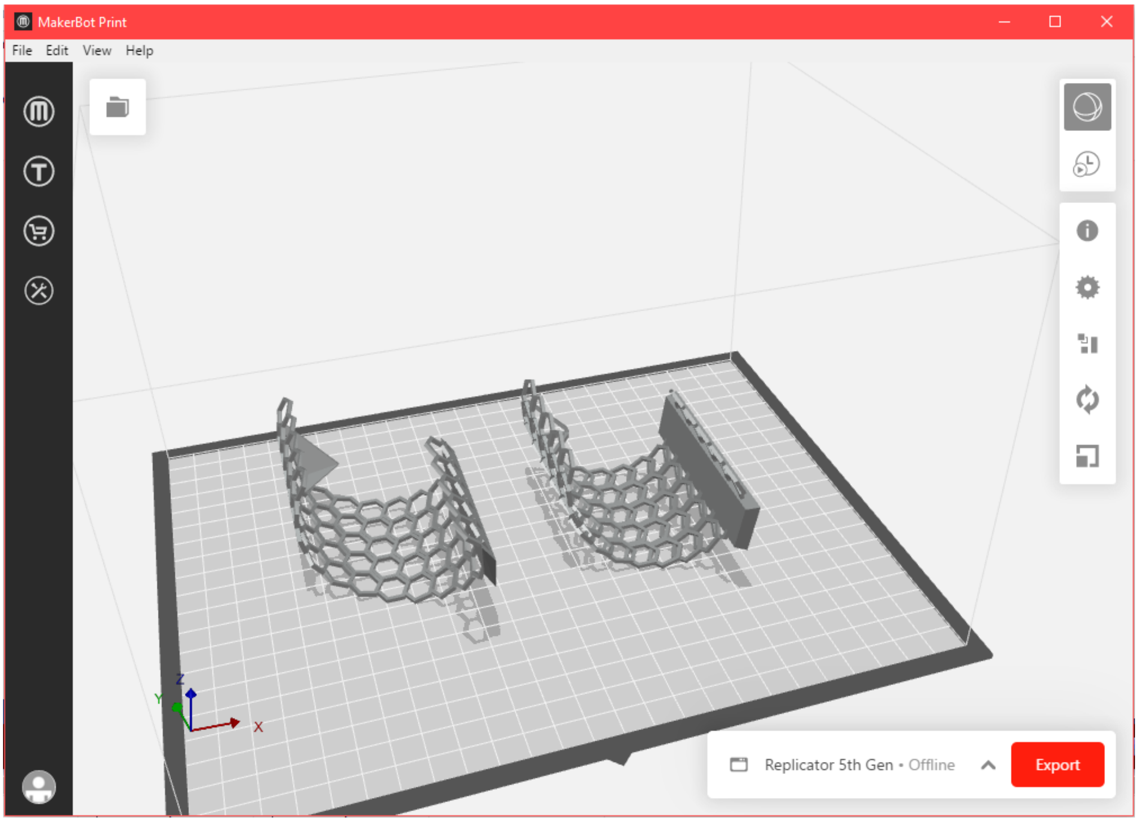


Figure 27: *Product Placement on the Printing Bed.*
Blender (left) and SolidWorks (right).

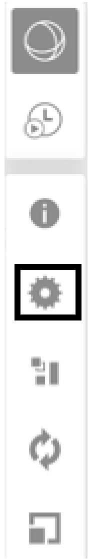


Figure 28: *Print settings are selected from the right-hand list of options.*

It is essential to check the boxes ‘Support’ and ‘Support Under Bridges’ as shown in the following figure.

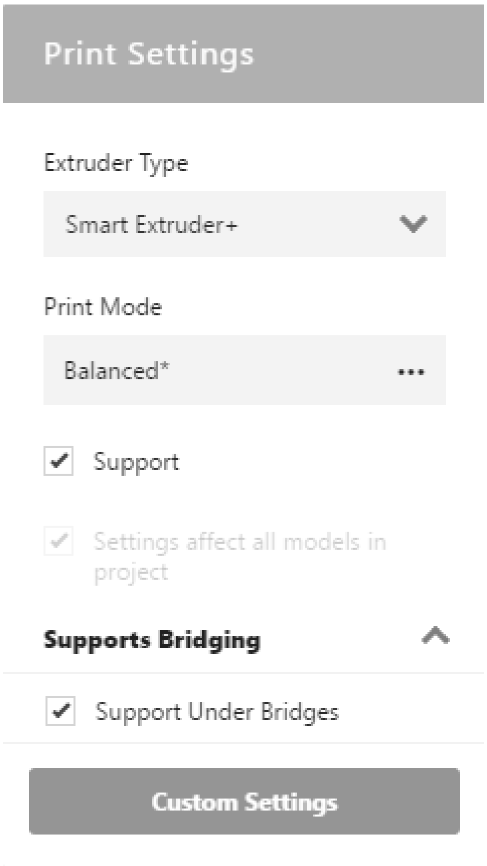


Figure 29: *Print setting dialogue window.*

Under ‘Custom Settings’ in the dialogue window select ‘Support + Bridging’. To stop the support from activating unnecessarily, the default ‘Support Angle’ was changed from 61° to 70°. Also select the ‘Raft + Base’ checkbox to enable the raft. Other inputs are left as they are. The setting inputs are shown as follows.

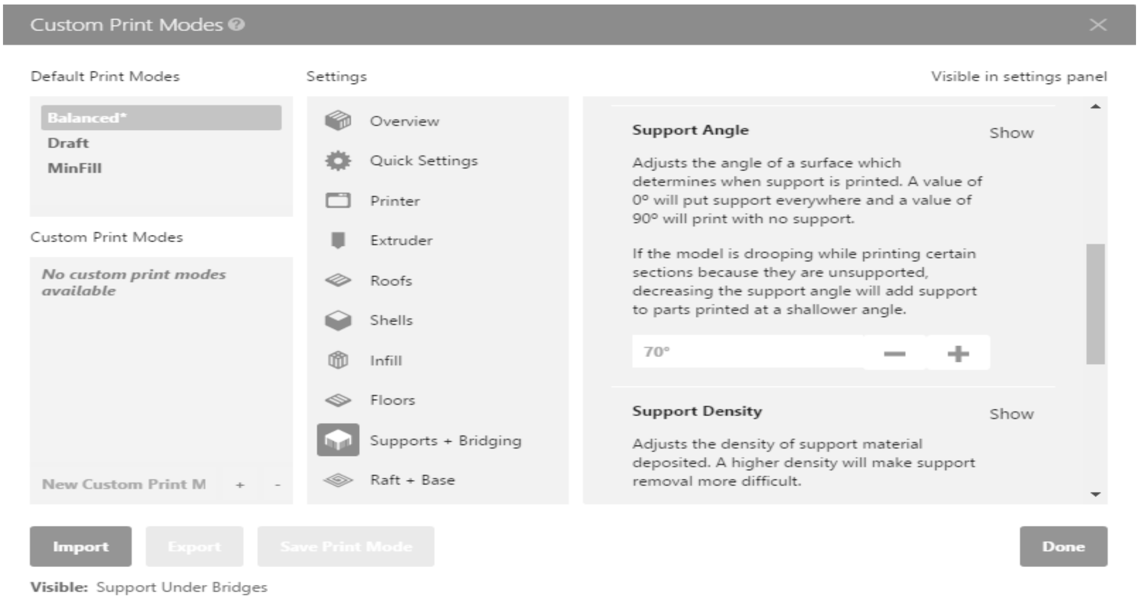


Figure 30: *Custom setting dialogue window.*

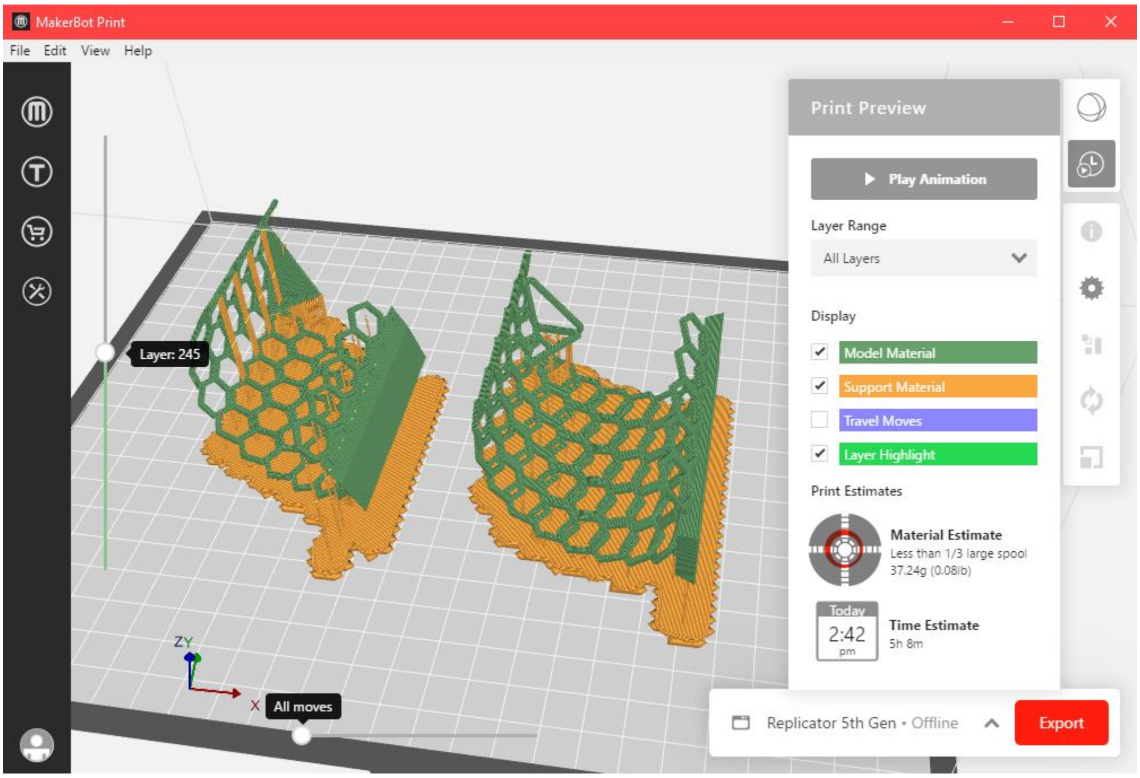


Figure 31: *Print review with raft and supports enabled.*
Blender (left) and SolidWorks (right).

It took approximately 2-4 minutes to remove the rafts and supports from each model as they were easy to remove. SolidWorks model took a little more time to clean, compared to Blender's because of the complex structures of the overlapping honeycombs.

The following figure shows a photo taken right after printing, using a different printer from MakerBot, as it conveniently visualizes how the model was placed onto the printer's bed.

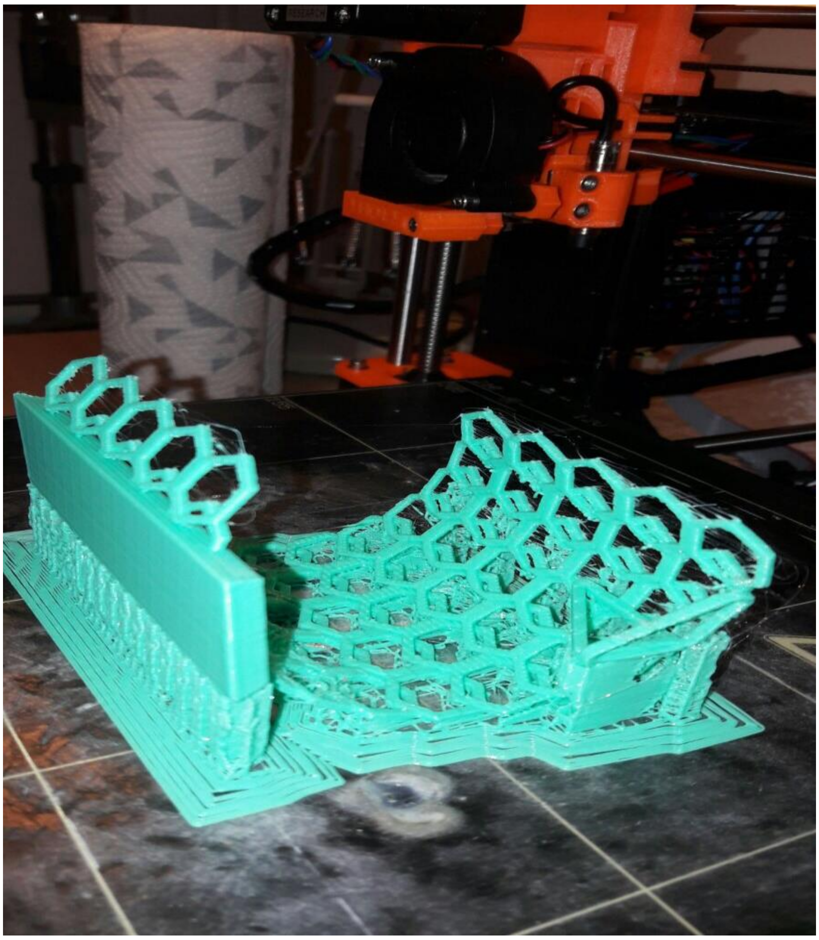


Figure 32: *Model placement on the Prusa i3 MK2 3D Printing bed.*

4 RESULTS

4.1 Program reviews

Table 2: *SWOT analysis for Blender*.

STRENGTHS (internal factors, positive points)	WEAKNESSES (internal factors, negative points)
• Professional powerful modelling program. • Free of charge, open sourced, updated frequently. • Can be run on both Windows and Mac, lightweight, no installing. • Multifunctional designing purposes (sculpting, rigging, rendering, simulation and animate films). • Blender uses mesh based object, thus has a very dynamic method of designing and is capable of designing both mechanical and organic/natural models.	• Blender is hot-key oriented, meaning users will need practice to remember the hotkeys when using Blender. • The interface is notably complex. • The number pad keyboard and middle mouse wheel are essential, thus a desktop computer is much preferred to a laptop. • Blender's versatility makes it a good choice for everything regarding graphic applications. However, it is barely a replacement for the other software that offer niche products. • Tutorials are plentiful; yet, they are all spontaneously produced by enthusiasts.
OPORTUNITIES (external factors, positive points)	**THREATS (external factors, negative points)**
• Blender has a dedicated online community that is keen on helping each other. • Blender's open-source nature allows users to recode and keep Blender updated for a better version.	• Blender-cloned software appears. • People take upon themselves to create tutorials for Blender for lucrative purposes, which goes against the principles of the sharing nature of the software.

4.1.1 SolidWorks

Table 3: *SWOT analysis for SolidWorks.*

STRENGTHS (internal factors, positive points)	**WEAKNESSES (internal factors, negative points)**
• Professional parametric modelling program. • One of the mainstream industrial-grade programs that is widely used. • Fundamental tutorials can be found within the program, which are organized and classified into categories. • SolidWorks is a parametric designing software, thus it is best suit for mechanical models and manufacturing purpose.	• The cost is considerable. • Features could be redundant for non-professional designers. • Steep learning curve. • Ability to design organic objects; however, the possibilities are limited.
OPORTUNITIES (external factors, positive points)	**THREATS (external factors, negative points)**
• Knowledge and skills in SolidWorks can benefit users greatly, regarding a professional engineering career.	• Subsequent software equipped with the full tool set of a parametric software, i.e. Onshape etc., that are more easily accessed, can take the place of SolidWorks.

4.1.2 AHP method

The SWOT analysis covers the compositions of both software comprehensively, however; the analysis is limited to the software's the internal factors, and because of this, the Analytic Hierarchy Process (AHP) is employed.

AHP is used not only to complement the SWOT analysis but also aims at assisting users to obtain a clearer picture of the expected outcome, regarding the determined goals, during the defining process among the possible options.

AHP is a useful analytical tool and is backed-with-scientific methodology for multi-criteria decision making, thus creating a helpful foundation for all logical choices in life.

In the following figure, the goal of the thesis is emphasized as the global goal, and then subdivided into criteria and sub-criteria with respect to all the aspects of a CAD software that can benefit the designer, regarding modelling. There are other features such as rigging, animation, video making or simulations but they have been understandably omitted, as they do not relate to the current work.

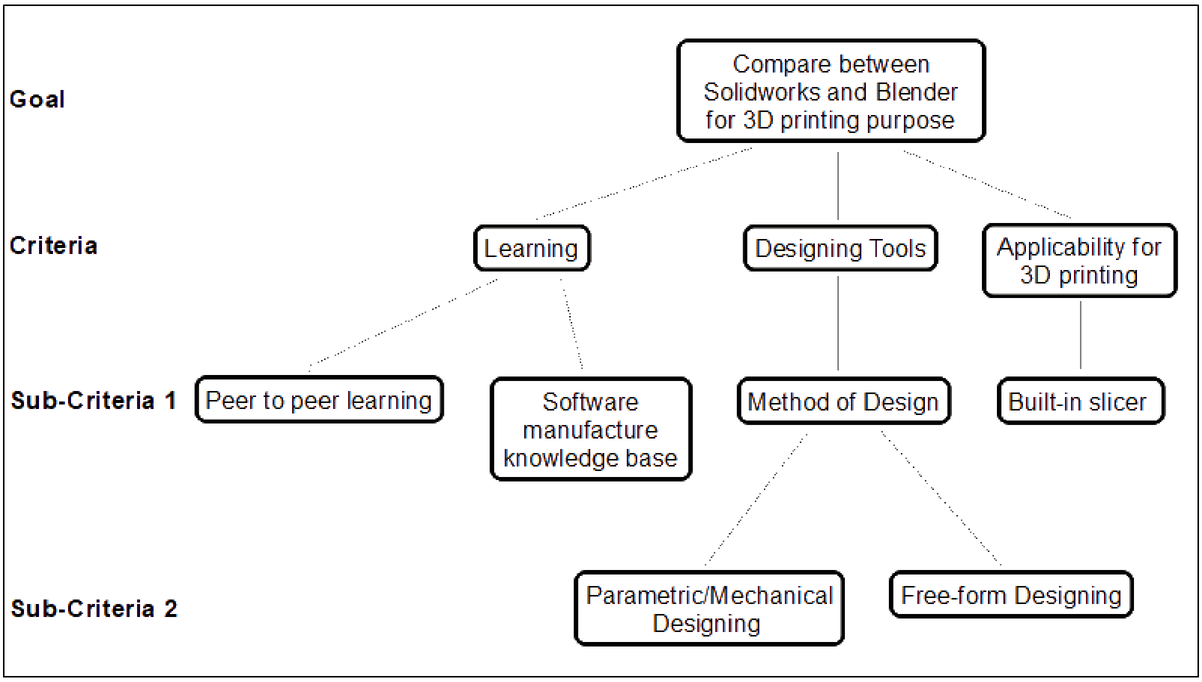


Figure 33: *Overview of the Analytic Hierarchy Process.*

Normally, users would know which criterion is the most important to them, but it is not always immediately obvious how much more valuable one criterion is over another. The AHP priority calculator prioritizes the criteria and systematically ranks them, showing how much they contribute to the final goal based on a predefined method of logical algorithms.

The following figures show screenshots with the inputs that have been added to an AHP calculator fields to make the pairwise comparisons between the three most important criteria in this study. Users following this analysis for themselves may need to check the consistency several times (See the 'Check Consistency' button under the comparison list for checking the comparison each time new valves are added) and adjust the alternative values between the compared intensities (1-9) under the column heading 'How much more?' to satisfy the logical norm. An alert will appear and suggested values will be highlighted, if the calculator finds the values put into the fields are not within the permitted limits.

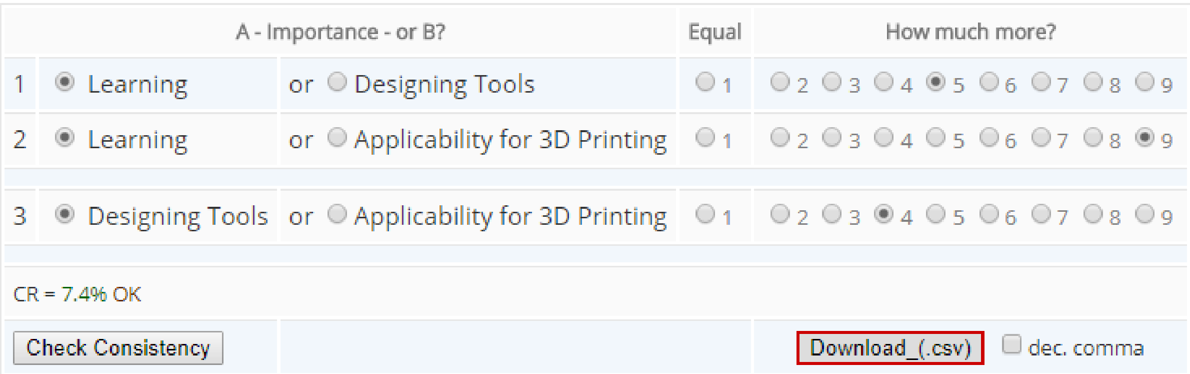


Figure 34: *Pairwise comparison between main criteria.*

AHP Scale: 1-Equal Importance, 3-Moderate Importance, 5-Strong Importance, 7-Very strong Importance, 9-Extreme Importance (2,4,6,8 values in between).

The algorithms used by this programme have been established specifically for analysing prioritization of the categories shown below. After the inputs have been checked for consistency, a ranked priority list is displayed showing each criterion as percentages of the whole criteria.

Category		Priority	Rank
1	Learning	74.3%	1
2	Designing Tools	19.4%	2
3	Applicability for 3D Printing	6.3%	3

Figure 35: *Ranking result and intensities of the criteria [47].*

All the inputs shown above are fluid and can be changed according to personal preferences. As well as this, the number of main criteria and sub-criteria are not limited.

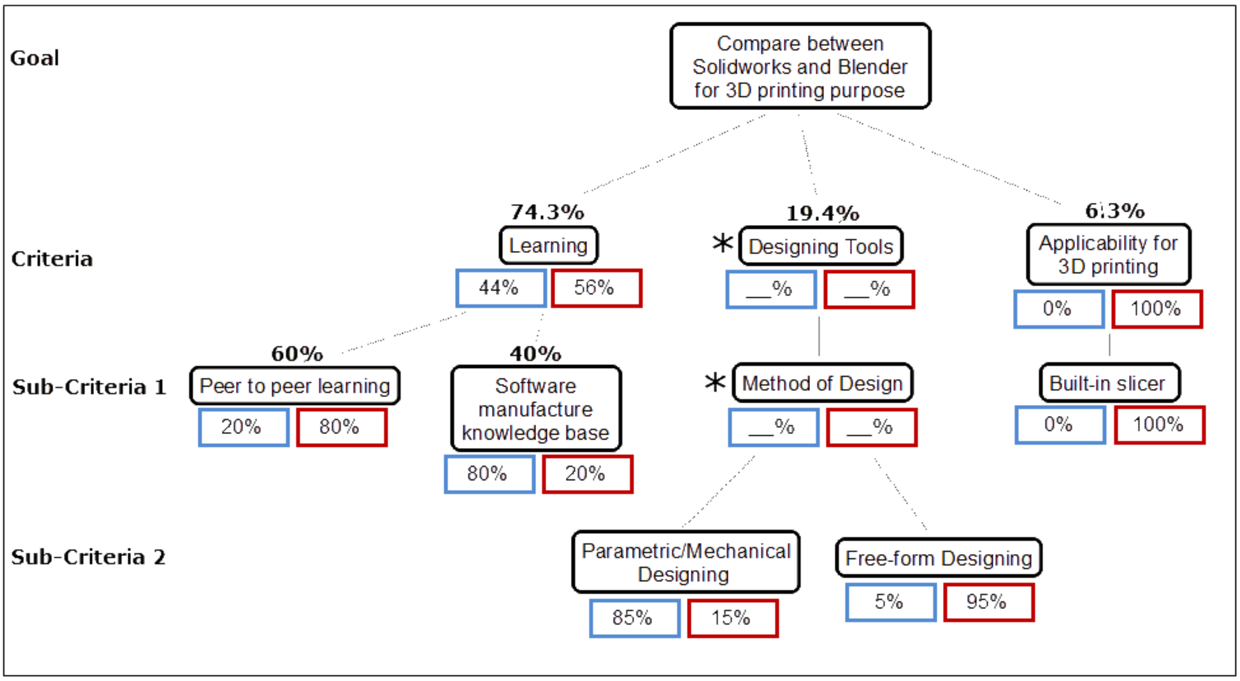


Figure 36: *Hierarchy in detail.*

The contribution of SolidWorks represented as a percentage,

The contribution of Blender represented as a percentage.

The criteria marked with an asterisk (*) designates values that vastly depend on the designer who may prefer one way of designing over another, as well as this the design of the given model plays an essential role in deciding how these criteria are valued.

Following the hierarchy in detail, we can calculate the contribution of each software as:

- Under "Learning":

  SolidWorks: 0.2 * 60% (Peer to peer learning) + 0.8 * 40% (Software manufacture knowledge base) = **44%**

  Blender: 0.8 * 60% (Peer to peer learning) + 0.2 * 40% (Software manufacture knowledge base) = **56%**

- Under "Applicability for 3D Printing" there is only one criterion, Built-in slicer, which Blender has the SolidWorks does not, thus Blender contributes **100%** and SolidWorks contributes **0%**

- Under "Applicability for 3D Printing" and "Learning":

  SolidWorks: 0 * 6.3% (Applicability for 3D Printing) + 0.44 * 74.3% (Learning) = **32.692%**

  Blender: 1 * 6.3% (Applicability for 3D Printing) + 0.56 * 74.3% (Learning) = **47.908 %**

Interestingly enough, without the "Designing Tools" counted in, the overall score of Blender is 47.9% and SolidWorks is 32.7% (over 80.6%), which is an almost winning situation for Blender regarding the goal and criteria stated.

4.2 Product reviews

4.2.1 Blender

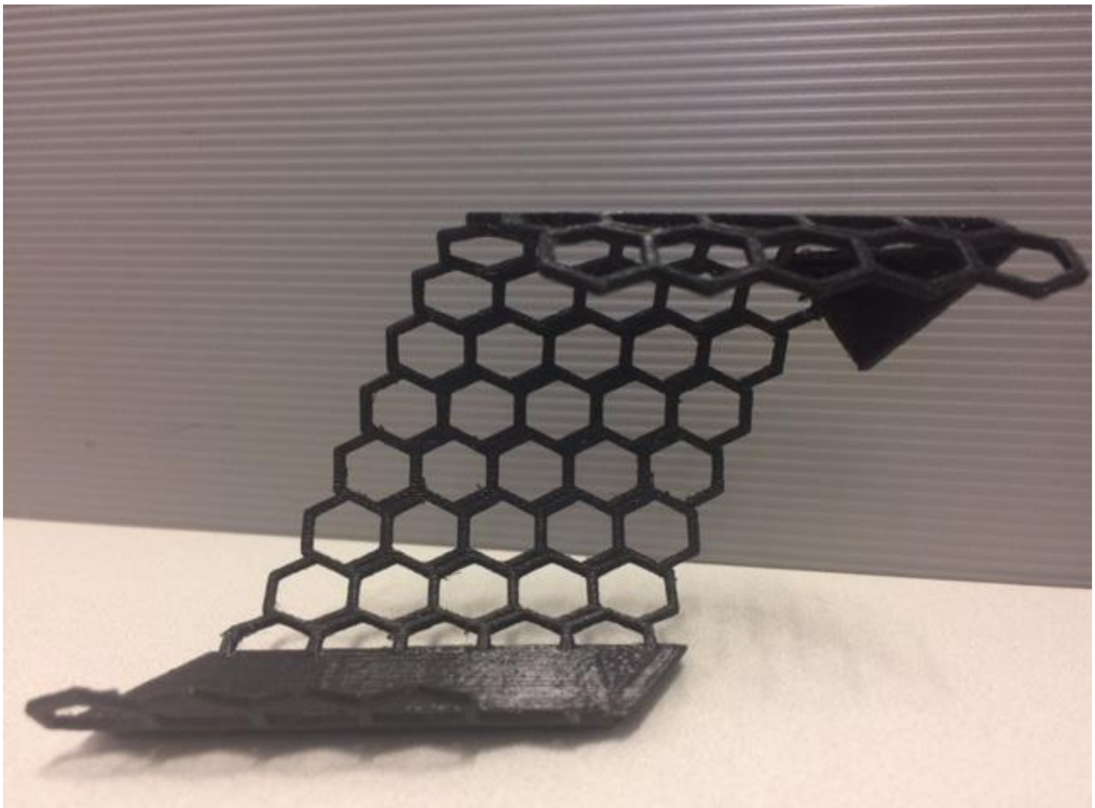


Figure 37: *3D printed product designed with Blender.*

- Product information: The business card holder construction was designed using a smooth hexagonal net formed into a cylindrical shape. This made the removal of the supporting structure a simple matter.
- Dimension (height x length x width): 61.9 x 108.8 x 48.5 mm.
- Material used: 17.8 g.

4.2.2 SolidWorks

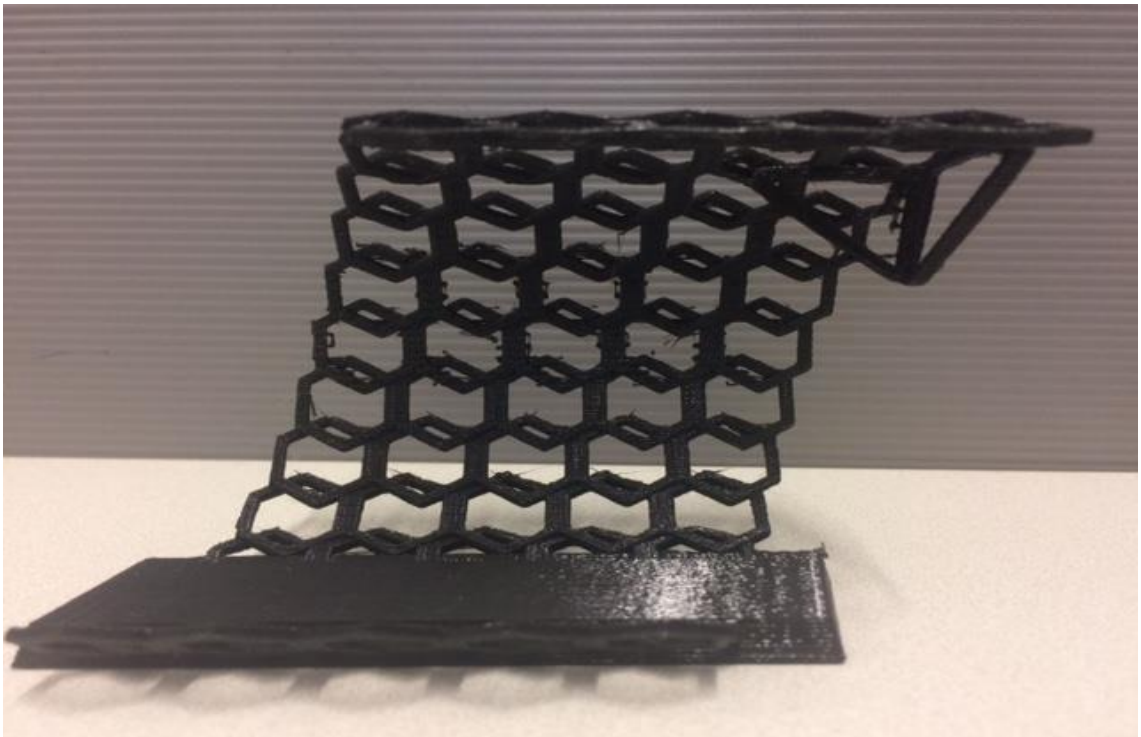


Figure 38: *3D printed product designed with SolidWorks.*

- Product information: The business card holder construction was designed using a network of flat overlapping hexagonal rings formed into a cylindrical shape, as SolidWorks functions did not obviously allow a smooth cylindrical form to be created. This made the removal of the supporting structure difficult.
- Dimension (height x length x width): 69 x 132.9 x 57.5 mm.
- Material used: 23.26 g.

Figure 39: *An example of the products in practical use.*
SolidWorks (left) and Blender (right).

5 DISCUSSION

Chronologically, this business-card holder model for 3D printing was first designed with Blender, which was initially a software product completely unfamiliar to the author. It was selected in order to take advantage of Blender’s vast array of graphic tools and to see how diverse its functions could be and also test its limits. The same design was then later recreated using SolidWorks. The model was designed by both software products as a natural shape rather than as an engineering model, giving rise to this eccentric design, which is rarely done in the case of SolidWorks. At first glance this business-card holder may appear as a not-so-practical free-form shape; however, it proved to be a viable design.

The applicability of each software product for 3D printing is in conclusion identical, as the post-designing processes are treated equally, using one slicer program to slice the resulting STL files created by each product.

The printed results proved to successfully replicate their digital files. Nevertheless, results depend enormously on each individual printer’s parameters and each slicer used to realize the final product.

During the process, a Prusa i3 MK2 3D printer was employed to perform the task of printing the models. However, since it was a brand-new private printer, companied by the lack of experience handling this type of printer, it took a couple of hours to figure out all the parameters to successfully begin the first print. Interestingly, the author found out it was easier to achieve a better printing quality by switching from the Prusa printer’s recommended slicer Slic3r, to Cura, which is a more widely used slicer designed to be compatible for a wide range of printers. From this initial experience of creating models on a 3D printer, it is worthwhile mentioning that beginners, enthusiasts and hobbyists should consider obtaining a sound prior practical knowledge of 3D printers and printing, in addition to familiarizing themselves with CAD files, including the STL files used by the slicers.

In cases where a printing platform is required, designers must inevitably have a slicer installed. Since the slicer is a stand-alone programme used to translate CAD files to G-code for the 3D printer to understand what is required, the slicer will also automatically detect design incompatibilities in models, as well as making adjustments for overhangs, manifolds, fill areas, wall thicknesses, plate adhesion, etc. before creating and exporting the G-code files. The capabilities of well-made slicers can save designers much time, in situations where there are printing problems with a model.

A plus for Blender 3D printer users is that for printing purposes, the software already has a “3D Tool Box”, a dedicated built-in slicer add-on.

6 CONCLUSION

3D printing is rapidly evolving and there are many who wish to access and understand the plethora of diverse and specialized information that accompanies this new phenomenon, and because of this, this work has been designed to enlighten users on one of the many aspects of 3D printing as well as giving the reader a general overview of the related subjects.

From the 3D printing and the additional contributing equipment and software, both central and peripheral, which need to be reviewed and scrutinized, this work concentrates specifically on CAD software's modelling capabilities, by example; and its essential ability to create good G-code to enable the models to be 3D printed successfully.

Different manufacturers have produced an extensive variety of software to accomplish this, and after careful consideration, for inclusion in this work, the chosen software to be review was finally trimmed down to two noticeably different products: SolidWorks and Blender, and then after employing this software, critical comparisons were made between SolidWorks' and Blender's printed models. The software were also compared using SWOT and AHP, which not only allowed a scientific approach, it also showed the user how, for example, the AHP calculator can be used if the criteria differs for the user's modelling purposes or the user's preferences. AHP's flexibility allows the tool to compare between three or more software, printers, choices of life, or just about anything under concern with multi alternatives. All in all, this work has generated a comprehensive objective overview of this software and compares all of the different possibilities, regarding their Computer-Aid-Design software capabilities for 3D printing purposes.

There is a final aspect to consider when one selects CAD software that relates more to the personality of the individual user. Regarding Blender and SolidWorks, the user with an engineering inclination would find SolidWorks more comfortable to use and more in line with-his/her way of thinking, while for the same reasons Blender appeals to the more artistically inclined designer.

It is hoped that this work encourages potential 3D printer users and designers to see the diversity of CAD design programs and choose wisely the most suitable program to accommodate each user's personal creative talents and abilities, and the type of 3D printing they intend to pursue. The model used in this work was deliberately more demanding than an average piece of engineering to show the capabilities of the programmes; however, the results of this work applies equally to more simple straight forward model designs. This thesis has been created at this point in time, which is still early years in the realm of 3D printing, but the principles it has established will be valid for the future; however rapidly the frontiers of technology are being pushed forward.

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