Product Design with Cloud Based and Desktop CAD Software

A comparison between SolidWorks and Onshape

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Abstract:
As mechanical computer-aided design (CAD) software keeps growing, which results in the broad influence of additive manufacturing in various industries. This phenomenon has changed the traditional methods of prototyping and production. As a result, mechanical CAD software takes an important role in product design. Even though desktop CAD software is improving and developing throughout the years, designers and design engineers are facing numerous challenges such as the conflict in versions, costs in hardware and license. The availability of cloud-based CAD software, offers a solution to its users, a service that requires no software installation, no conflict in versions and license. However, the ability of cloud-based CAD software is still in question, whether cloud-based CAD software can fully replace traditional desktop CAD software or just a supplementary tool. Thus, this thesis studies two parametric modeling software: SolidWorks (desktop CAD software) and Onshape (cloud-based CAD software). To examine the performance of each software, the author will employ both software to create an identical model where the strengths and weaknesses in the features and functions of respective software shall be revealed. Moreover, the author processes these models to a 3D printer to evaluate the final products from each software. In order to have a rational judgment, the author employs two analysis methods, SWOT analysis and the AHP model to analyze which software is more suitable for designers and design engineers. This thesis work is a case study on two prominent software, from the product design perspective to prototyping final products; it also demonstrates many factors that one need to take into consideration in order to find the most suitable software for their design goal.

Keywords:	Mechanical CAD software, desktop CAD software, cloud-based CAD software, SolidWorks, Onshape, 3D printing, product design.
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CONTENTS

Figures

Tables

List of Abbreviations

ABS	Acrylonitrile butadiene styrene
AHP	Analytic Hierarchy Process
AR	Augmented reality
C.R	Consistency ratio
CAD	Computer-aided design
CAM	Computer-aided manufacturing
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
MCAD	Mechanical Computer Aided Design
NURBS	Non-Uniform Rational B-Splines
PDM	Product data management
PLM	Product lifecycle management
SaaS	Software system, which performs as a Software-as-a-Service
SDRC	Structural Dynamics Research Corporation
VR	Virtual reality

List of Symbols

λ_{max}	The Principal Eigenvalue
n	The Number Of Criteria
C . I	Consistency Index
C.R	Consistency Ratio
R . I	Average Random Consistency Index
| A |	Pairwise Comparison Matrix
$\boldsymbol{w}$	Vector Of Relative Weight
$\boldsymbol{w_s}$	Weight Sum Vector

FOREWORD

It has been a long journey since the first day I started my study at Arcada University of Applied Science. During my study, I have met and learnt so much from my teachers and my classmates. It is an honor to pursue my higher education at Arcada. I have learnt a wide range of skills including advance knowledge in polymer chemistry, mathematics, physics, mechanics, mould design and 3D printing technology. As a curious person, I have a strong urge in learning new things; modelling software and 3D printing are my favorite subjects that I would like to learn to my heart's content.

However, when I encountered 3D modelling software and 3D printing technology, I found out that it requires a lot of time and effort to be proficient in using the software and to be able to model a functional product. Even though mechanical CAD software and additive manufacturing technology have a long history, the useful information is scattered. Therefore, I would like to choose a case study of two well-known CAD modelling software as my thesis topic. I hope that my thesis work would present an informative understanding of CAD modelling software and 3D printing technology that I have learnt during my study. Although there are many limitations in the thesis, I hope this could encourage other keen students to practice more on CAD modelling software, which would advance their professional career in the near future.

As it takes considerable time and effort to complete this work, I would like to express my appreciation to my thesis supervisor, Mr. Mathew Vihtonen for his valuable and constructive suggestions during the writing and development of my thesis. His dedication to students throughout his instructive teaching has been very much appreciated. I would like to thank Mr. Nigel Kimberley, for his advice and support in editing and improving my writing. My gratefulness are also extended to Mr. Stewart Makkonen-Craig for his inspiring teaching style that motivates students to not only studying theories in the classrooms, but also putting the theory into practice.

Finally, I wish to thank all my friends, my beloved ones for their mental support and encouragement during the course of my study.

1 INTRODUCTION

1.1 Background

There is a wide understanding within engineers that traditional method requires well comprehension in product design, mould design and materials selection. Thanks to computer-aided design (CAD) software and additive manufacturing (AM) technology, custom design is no longer challenging for production. Keen engineers and designers now can use CAD software to design any objects base on individual needs. Meanwhile, AM technology allows 3D printers to print any objects in complicated shape. In other words, CAD software changes traditional production method. Designers and manufacturers are now able to develop innovative products and production systems (Wei Gao, 2015).

Within the last two decades, CAD software develops rapidly. From advanced drafting and engineering functionality, CAD software is now interested in PDM (product data management) and PLM (product lifecycle management), which reduce concept design and manufacturing time (Bethany, 2017). Together with the development of the Internet in the late 2000s, Ford Mondeo was designed over the internet by using Ford's C3P (CAD/CAM/CAE/PDM) platform. The progress was reduced one third of the traditionally required time (Winter, 1999). Clearly, the integration of CAD and the internet could offer engineers and designers the best solution to collaborate and work in an efficient way. As a result, many companies attempted to release their first web-based CAD software. For example, Alibre released Alibre Design in 2000; AutoDesk released AutoCAD 2000i.

Moreover, the rise of using CAD in many industries in the 21st century brings a new trend in CAD industry, the cloud-based CAD. This trend becomes a popular topic after SolidWorks featured it at their event World 2010 (Johnson, 2010). Cloud-based changes the workflow in the whole CAD industry. Engineers and designers around the world can work simultaneously on a CAD model. To catch up with the new trend, AutoDesk released Fusion 360 in 2013; Onshape was available in 2015; and SolidWorks introduced SolidWorks Xdesign beta in the spring of 2016 (Bethany, 2017) (Mings, 2016).

As the development of internet and cloud-based CAD software, the availability of CAD software is spreading across industries. Despite of its drawbacks, cloud-based CAD software will evolve and change the traditional production method. Together with other new trends, such as augmented reality (AR), virtual reality (VR), generative design, it is possibly that cloud-based CAD software may replace desktop CAD software in the next decade.

1.2 Objectives

This thesis targets mainly on users with intermediate skill in using CAD software for education purpose or public design projects. The main purpose of this study is to compare a desktop CAD software (SolidWorks) with a cloud-based CAD software (Onshape), in order to identify which software is more functional for users, especially engineers. This main objective can be analyzed in four specific objectives as following:

- To model a part in both software, SolidWorks and Onshape
- To examine each design in SolidWorks Simulation (a simulation package of SolidWorks) and Simscale (a simulation cloud-based software that has partnership with Onshape)
- To 3D print the design and examine the final printing products
- To analyze the applicability of two software regarding its functions by using SWOT analysis and Analytic Hierarchy Process (AHP)

1.3 Relevance to Working Life

Among many mechanical computer-aided design (CAD) software, SolidWorks is renowned for its professional features and its friendly user interface, compare to other similar CAD program such as CATIA. Hence, SolidWorks is not only commonly used in academic institutions but also among mechanical engineers and designers. Moreover, SolidWorks offers a reliable certification program for design engineers and designers that want to be distinguished from others. The certifications cover a wide range of skill levels from beginner to expert. It is highly recommended for engineering students who wish to enhance their skills to obtain SolidWorks certifications in order to advance their professional career in the near future.

As an engineering student who is enthusiastic about mechanical modelling software, the author noticed that the accessibility of SolidWorks is one of those few obstacles for engineering students to spend more time practicing on SolidWorks. Since SolidWorks program offers a professional user interface, the software requires a powerful workstation to be fully functional. This means users have to invest not only in software license but also in hardware configuration. Besides hardware cost, the conflict between software version is another issue users may have to keep in mind when working on a project. For these reasons, a cloud-based software that offers designers and engineers a solution to maintain smooth workflow and provide similarly professional interface, is a great alternative.

However, cloud-based modelling software is a new service that still in debate whether it meets users' demands. As a result, this thesis work specifies both strengths and weaknesses of desktop CAD software and cloud-based CAD software; presents a general picture about the growth and improvement of CAD modelling software. Moreover, the author hopes that this work would assist more enthusiastic engineering students to gain a full insight into CAD modelling software.

1.4 The relationship to existing knowledge

In Arcada, Plastics Technology students are proficient in using SolidWorks, understand how to model an object, work with bill of materials, as well as prepare a 3D printing file from SolidWorks. However, when using a SolidWorks Education version, students may have limited access to other functions such as Product Data Management and Advanced Simulation, which students may encounter at the workplace. Meanwhile, Onshape is a SaaS (Software-as-a-Service) that share a similar user interface to SolidWorks that not only offers a full cloud-based CAD software system, but also introduce a user-friendly approach to students who want to learn more about Data Management. Additionally, Onshape provides its users plenty of interactive tutorials online from beginner to advanced level. These tutorials cover a variety of skills such as sketching, modeling parts in Part Studio, creating assemblies and 2D drawings. Thus, in this thesis work, the author would like to propose a case study on SolidWorks and Onshape to gain an understanding of both modelling software in order to find which software is more suitable for Plastics Technology students.

2 LITERATURE REVIEW

2.1 Mechanical Computer Aided Design software (MCAD software)

Mechanical computer aided design software (MCAD software) has a long history from 1957 when Dr. Patrick J. Hanratty developed PRONTO (Program for Numerical Tooling Operations), that is the first commercial numerical control programming CAM (computer-aided manufacturing) system (FreeCAD, 2013).

During 1960s, many companies developed their first commercial CAD programs, such as SDRC (Structural Dynamics Research Corporation), Evan & Sutherland, Applicon, Computervision, and M&S Computing. By the 1970s, Dr. Ken Verspille invented NURBS (Non-Uniform Rational B-Splines) for his Ph.D thesis, which formed the basis of modern 3D curve and surface modeling (Cohn, 2010). With the development of UNIX workstations in the early of 80s, CATIA, AutoCAD and other commercial systems was released during this period and appeared in aerospace, automotive and other industries. AutoCAD took a significant role in the evolution of CAD. The program increased the advanced drafting and engineering functionality, and became more affordable. Even though AutoCAD was the pioneer of mechanical modelling software, AutoCAD is mainly a 2D design software. Until the 1990s, the development of the PC qualified enough to perform 3D CAD on Windows. SolidWorks released its first software in 1995; it was the first solid modeler for Windows.

The modern CAD software has grown rapidly in the early of the 21st century, companies concerned more with Product Data Management (PDM) and Product Lifecycle Management (PLM) that reduce manufacturing time and increase workflow (Bethany, 2017). However, the traditional CAD and PDM cannot functional well in distributed teams, which require "the long file-copying process" (Hirschtick, 2015). Therefore, Jon Hirschtick, co-founder Onshape, decided to change "the fundamental architecture of CAD" (Hirschtick, 2015): release a full-cloud CAD software system. According to Jon, Hirschtick, there is no version control (users can work on the latest version, no copies, one version for everyone), no design conflicts (many users can modify the same design simultaneously by whichever device they use – computers, phones, or tablets).

Generally, an original MCAD software offers capabilities in 3D modelling, 2D sketching, assembly modelling, and engineering documentation. Modelling and sketching abilities can be classified into two approaches, depend on users' purposes: parametric and direct sketching modelling.

- Parametric sketching & modelling: In term of parametric, when the dimension value is modified, the shape of model geometry is changing immediately (DesignTech, N/A). In sketching, parametric dimensions fully define and control 2D entities (Lifecycle Insights, 2018). In parametric modelling, a standard geometry definition, which is called feature, is the basic unit of a parametric solid model. These features create and modify geometry in parametric modelling. Parametric models use features-based approach that allows designers to alter one parameter, the two other parameters then adjust automatically.
- Direct sketching & modelling: In direct approach, 2D entities can be freely changed parameters within the assumptions of related geometry. In direct modelling, the features geometry can be modified without retaining the original definition. Direct modelling allows designers to push, pull, and twist the model while the geometry modified itself. (Lifecycle Insights, 2018)

Additionally, there are few software provide both parametric and direct modelling capabilities, such as PT Creo and Siemens NX (NxRev, 2016). Each approach to 3D modelling has its own pro and cons, yet engineers and designers would choose the most suitable software which offers the best use of all.

2.1.1 Desktop CAD software

2.1.1.1 SOLIDWORKS Modelling

In December 1993, Jon Hirschtick used his own funds (approximately $1 million) while he was a member of MIT BlackJack Team and established his company, SolidWorks. Later on, he recruited a team of engineers, in purpose of launching a 3D software, which was "accessible, affordable and available on Windows desktop" (Scan2cad, 2017). In November 1995, SolidWorks took the first step in the evolution of CAD, released the first 3D modelling for Windows. In 1997, Dassault Systemes S.A acquired SolidWorks was by and kept growing in the next two decades.

The availability of SolidWorks has changed the way engineers' creation methods. In the last two decades, SolidWorks launched 26 versions, focused on various disciplines such as 3D CAD, Electrical design, PDM, Simulation, 3DEXPERIENCE, and Technical communication. Thus, SolidWorks' applications spread over engineering and design industries such as, aerospace, construction, and manufacturing. (Scan2cad, 2017)

As a parametric modelling software, SolidWorks user interface is straightforward and user-friendly. According to SolidWorks Tutorial, users usually work with six main areas of interface include: Menu Bar, Command Manager, Feature Manager Design tree, Status bar, Head up view toolbar, Graphics area. (SolidWorks, 2018)

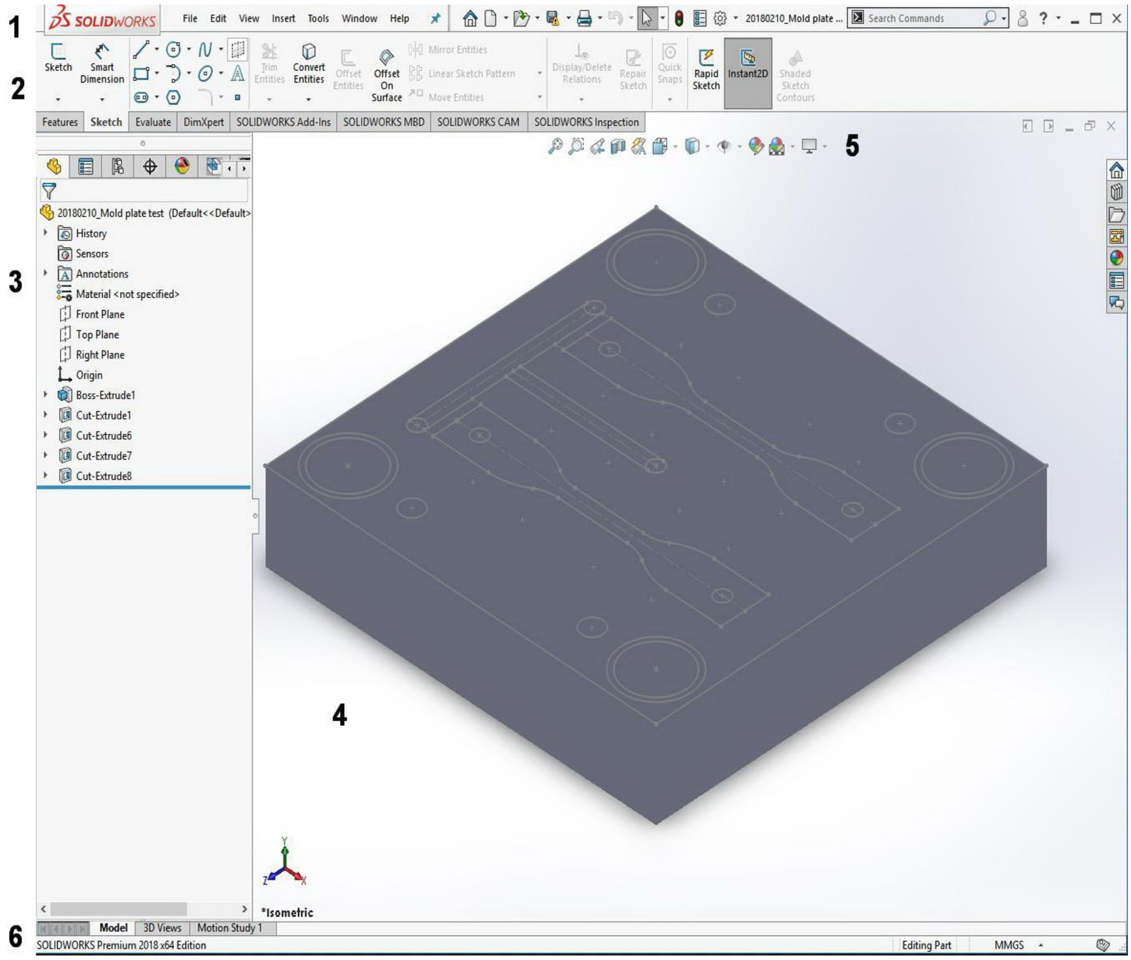


Figure 1. SolidWorks User Interface.

(1) Menu bar. (2) Command bar. (3) Feature Manager Design tree. (4) Graphics area. (5) Head up view toolbar. (6) Status bar.

2.1.1.2 SOLIDWORKS Simulation

According to SolidWorks, SolidWorks Simulation includes many packages which user can set up different virtual environment to test one's product design before manufacturing (SolidWorks, 2018). Recently, there are four main packages:

- SolidWorks Simulation Premium: includes simulating tools for nonlinear and dynamic response, dynamic response, and simulation for composite materials.
- SolidWorks Flow Simulation: mainly focus on fluid flow, heat transfer, fluid forces, and computational fluid dynamics.
- SolidWorks Plastics: analyses design plastic parts or injection mould design
- SolidWorks Sustainability: assess life cycle of parts or assemblies directly, see how a material affect environmental impact in real time, and document one's findings.

A standard user interface of SolidWorks Simulation includes Graphics area, Analysis Preparation Command Manager, Simulation Study Tree, Simulation Toolbar, and Expressions in Input Fields.

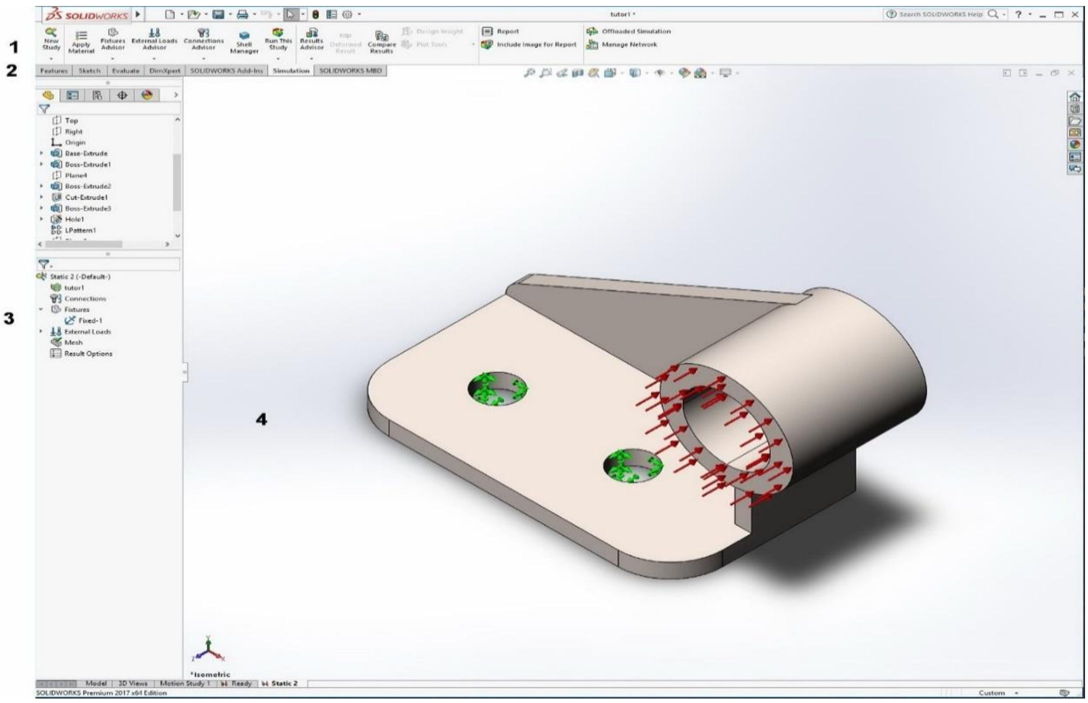


Figure 2. SolidWorks Simulation user interface.

(1) Simulation Toolbar. (2) Analysis Preparation Command Manager. (3) Simulation Study tree. (4) Graphics area.

2.1.2 Cloud Based CAD software

Technically, cloud CAD software is CAD software, which "runs in a browser or provides cloud services through an app" (AutoDesk, 2017).

2.1.2.1 Onshape

In 2012, John McEleney and Jon Hirschtick, former founders of SolidWorks, introduced their new company, Belmont Technology. After several years looking for venture funding, they changed their name to Onshape (CIMdata, 2014). The original team members include the key members of SolidWorks and "elite engineers from cloud, data security and mobile industry" (Onshape, 2016). In 2015, the company excitingly launched their Beta version of Onshape after six months pre-production testing in 52 countries (Hirschtick, 2015). Recently, Onshape proudly introduced itself as the only company provides full-cloud features (Onshape, 2016), a cloud-based CAD software system, which performs as a Software-as-a-Service (SaaS).

According to Onshape's brochure Press Kit 2016, users can access Onshape via web browser such as Firefox, Chrome, Safari or Microsoft Edge, as well as any computers run on Microsoft Windows, Apple Macintosh, or Linux. There is no downloads, installs, license keys, or service packages. Moreover, Onshape offers a free professional CAD service for students and hobbyists, who can create open and public projects with unlimited storage.

Even though Onshape share several similar features to SolidWorks, Onshape user interface aims to design, not document management (Corbett, 2016). Thus, there is no Save function, designs are updating and saving in cloud automatically. A standard Onshape workspace include a Part studio tab and an Assembly tab. The Assemble tab has the same workflow and function as SolidWorks. However, the Part studio can be a sketch, a part, a video clip or a document.

In user interface, Onshape not only shares some similar features to SolidWorks, but also introduces new features that assists users in a flexible approach, such as Merge/Branch features. Onshape's users usually work with six main areas include: Document Toolbar, Features Toolbar, Branch/Merge feature, Feature List, Graphics area, and Part Studio. These working areas were presented in figure below.

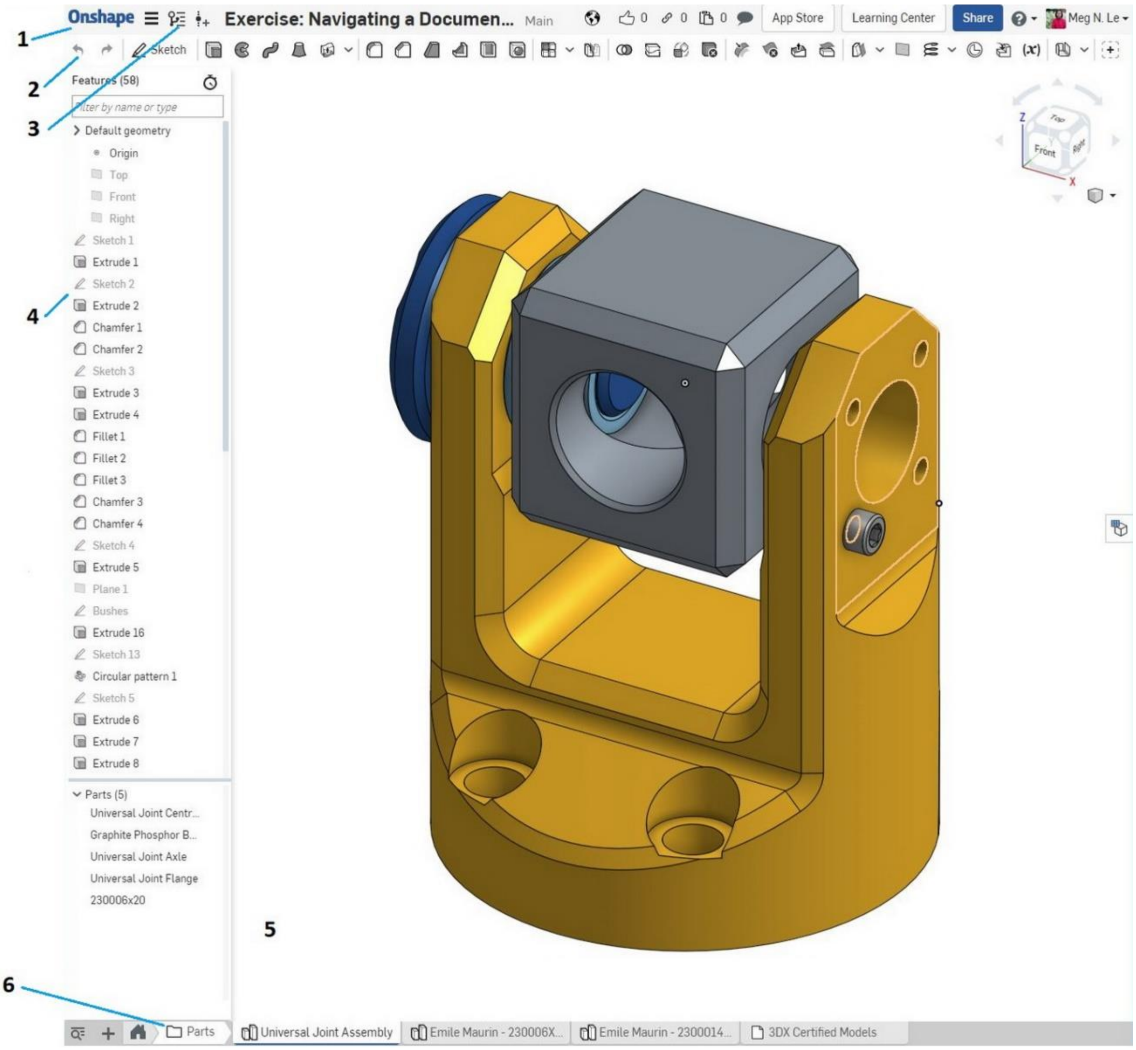


Figure 3. Onshape user interface on web browser

(1) Document Toolbar, (2) Features Toolbar, (3) Branch/Merge feature, (4) Feature List, (5) Graphics area, (6) Part Studio

Additionally, Onshape takes one-step further to reach its users by launching Onshape application that run on iOS or Androids. Users can operate Onshape Touch via mobile devices.

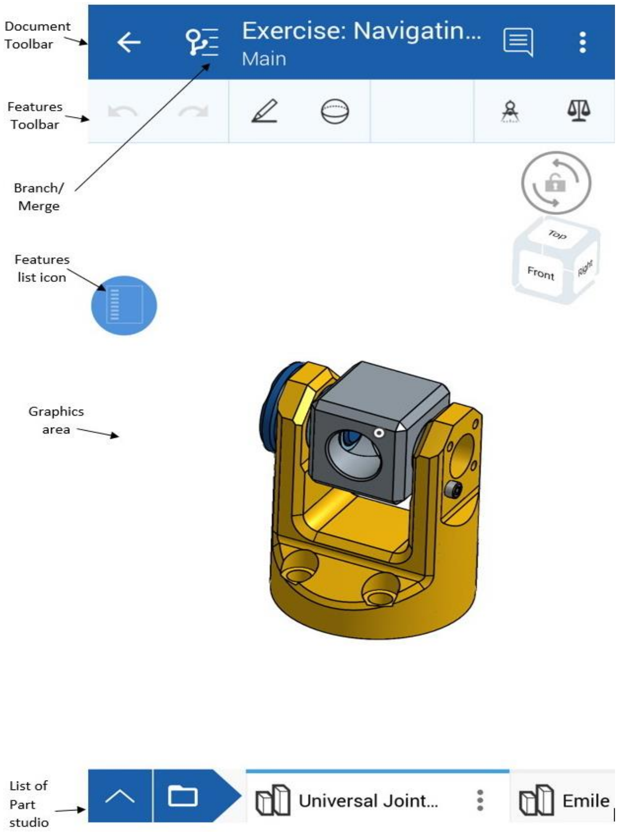


Figure 4. Onshape Touch user interface on Android phone

2.1.2.2 Simscale

Simscale is a cloud-computing product, which was developed by Simscale GmbH. As a partner with Onshape, Simscale provides simulation service include:

- Solid Mechanics Simulation (Finite Element Analysis - FEA): The FEA module uses the open-source code to perform simulation; there are two approaches: *physics perspective* and *solver perspective*. The physics perspective follows the standard analysis by employing the Code_Aster for this type. Meanwhile the finite-element analysis package CalculiX (CCX) only available in the solver perspective. (Simscale Static, N/A)
- Fluid Flow Simulation (Computational Fluid Dynamics - CFD): the simulation is performed using the OPENFOAM® software. OPENFOAM® is a licensed free and open source provided by OPENFOAM Foundation. (Simscale Analysis types, N/A)

- Thermal Analysis: Simscale offers two kinds of thermal analysis: Heat Transfer and Thermomechanical. Similar to the FEA module, the Thermal Analysis has two approaches: physics perspective and solver perspective. The physics perspective uses Code_Aster solver, and the solver perspective uses CCX. (Simscale Thermomechanical, N/A)

In Simscale, user can chose a various simulation. Users need to create a mesh of model before perform an analysis.

2.2 Products Design with Plastics

Traditional prototyping refers to sculpting, carving and machining. These methods are effective yet time-consuming, only suitable for mass production, and do not interact with CAD. Meanwhile, rapid prototyping approach, or 3D printing method interface with CAD software, allows designers, engineers to optimize products for manufacturing process. In the other words, keen engineers and designers can optimize a design, reduce printing time, add required strength and flexibility, decide whether a design needs support or bases, or choose the most suitable materials for products.

Most household 3D printers use a spool of plastic call filament, and these plastics are thermoplastics. When choosing the type of thermoplastics, users need to consider the printer's hardware. There are three considerable alternatives: 3D printers can print single thermoplastics, or multi thermoplastics, and printers neither have limitation on printing materials nor support any specific thermoplastics. For example, these are several most common thermoplastics:

- ABS (acrylonitrile butadiene styrene): high impact resistance, mechanical toughness, lightweight, can find in toys and consumer products.
- PLA (polylactic acid): the easiest material to print, biodegradable, offer printing product a well appearance
- Nylon (polyamide): good thermal and chemical resistance, a strong yet flexible and durable material, can find in mechanical parts and clothing.
- CPE (chlorinated polyethylene): highly heat resistance and chemicals, can find in automotive and moulding industries.

- PC (polycarbonate): a strong and tough material, available in transparent and limited solid colors.
- PP (polypropylene): a tough yet flexible material, low friction coefficient, can find in reusable food containers, living hinges.
- TPU (thermoplastic polyurethane): flexible, transparent and resistant to oil, can find in sporting and medical devices
- PVA (polyvinyl alcohol): a water soluble material, can pair with PLA or Nylon as a soluble support material
- HIPS (high impact polystyrene): dissolve in chemical limonene, can combine with ABS as a support material, or can be used as a primary printing material.

Among common thermoplastics, ABS and PLA are common materials in 3D printing. Later, nylon and CPE start to become popular among users. Different printing materials effect on both appearance and quality of final products, hence, it is important to understand properties of chosen materials.

There are two different kinds of build plate surfaces: hot (heated) and cold (unheated). Heated build plates are versatile; usually cover with a metal plate (glass or ceramic), and an additional surface materials such as Kapton tape, blue painter's tape, PVAc glue, glue sticks or PEI (polyetherimide). Heated plates can use with a wide range of thermoplastics, yet a slight expansion on the bottom edge of final products may occur after manufacturing process. Printing with heated plate also requires extra time for printing bed heating up and cooling down. Even though heated plate can optimized for variety of thermoplastics, the cost of heated plate can be expensive and increase the final costs of productions.

Meanwhile, unheated plates are more common in consumer printers. As the plates are made of reusable materials, such as plastic, glass, or metal, the unheated plates become the first choice of PLA prints. The additional surface materials for unheated plate can be a thin layer of glue stick or painter tape. It is possible to use other special surface treatment such as PEI and flexible plastic plate. Unheated plates are less cost and downtime compare to heated plate, however, unheated plates are less versatile, limited in printing materials. Only PLA and PLA composites are the primary materials for unheated plate.

Besides printing plates, build plate adhesion is another considerable perspective for a 3D printing part. There are two types of adhesion: raft and brim. Raft is a grid structure under printing part. Brim is a single-layer-thick flat area around printing part. Both raft and brim help printing object secure on the build plate and users can remove easily.

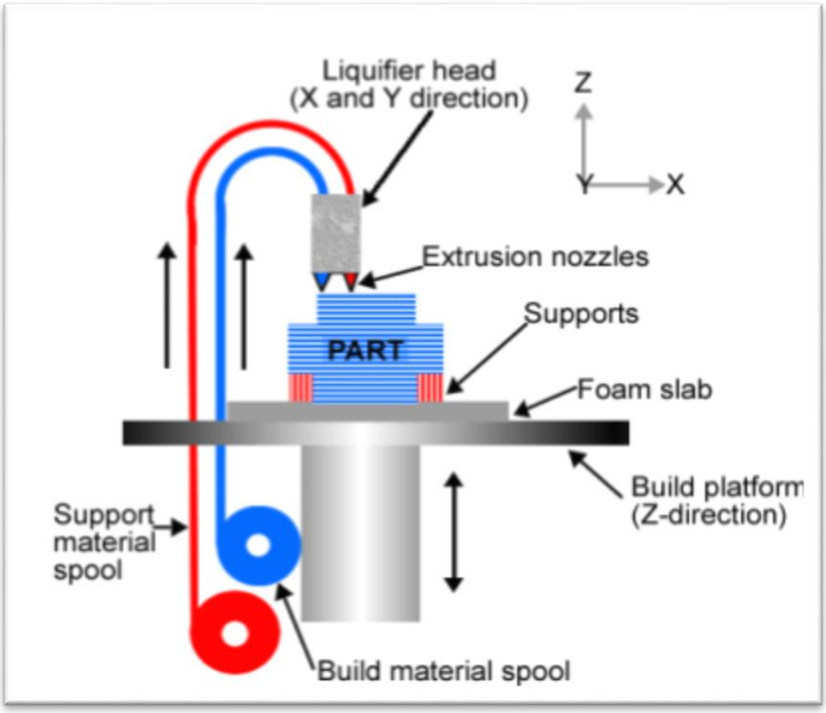
Inside a body of 3D part, the first layer is known as a floor or a bottom layer, is made up of one or more outlines, which is called wall, shell, or perimeter (Hultgren, 2018). These outlines contain solid fill. To control wall thickness, there are two options: control the dimension or the number of outlines. As a result, user can control the number of floor. Designer also can control the infill density and the pattern infill by adjust setting in 3D slicer software, such as Makerbot Print or Meshmixer. By increasing the infill density, the stiffness of the object increases. However, if designers want to save printing time, reducing number of shell or the infill density is an option.

2.3 Fused Filament Fabrication (FFF/FDM)

Among many additive manufacturing methods, Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) is technically an extrusion process. However, FDM is a trademark registered by Stratasys Company (Gebhardt, 2011, p. 45). Thus, RepRap project uses the term Fused Filament Fabrication to avoid legally constrained in its use. In term of FDM or FFF, the term Plastic Jet Printing also refers to this approach.

FFF method is the most common 3D printing method for household printer, an entry-level desktop machine. A motor pushes the raw material (usually thermoplastic filament) through an electric heating system and extrudes through a nozzle, deposits layer by layer on a printing plate until forming an object. During the process, the printing plate can move in X-Y-Z dimension, sync with the sliced CAD file.

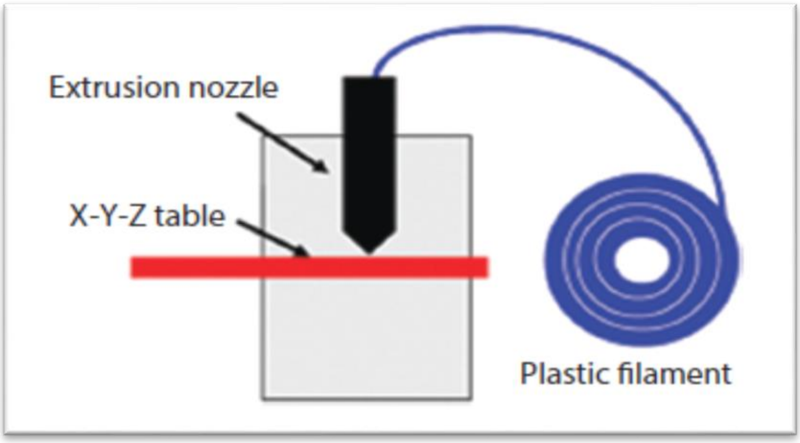
According to Gebhardt and Hötter (2016), after building a draft plane, the printing plate is lowered by the layer thickness; and the process continues again with the next layer. The distance between the extrusion nozzle head and the layer is from 0.127 to 0.330 mm. The gap between the nozzle head and the previous layer is set to about half of the nozzle diameter (Gebhardt & Hötter, 2016, p. 235). Moreover, there are two kinds of extrusion nozzle head: single and dual ones that illustrates in



and **Figure 6**. Consumers use 3D printer usually has one extruder to print one material at a time. On the other hand, industrial models often are high-end printers, which can print with a variety of production thermoplastics. These industrial printers can maintain an essential reliability and speed for industrial market. Even consumer-grade and industrial-grade printers has the same printing principal, however, there are several common differences between these two models:

- the number of extruders
- the number of materials – whether the printers can optimize one or several materials
- the size of the build plate
- the style of build plate - whether the build plate heated or unheated
- the kind of software – whether the models use proprietary or open-source software

Figure 5. Fused Deposition Modelling, Single Extrusion Scheme (Mastro, 2016)



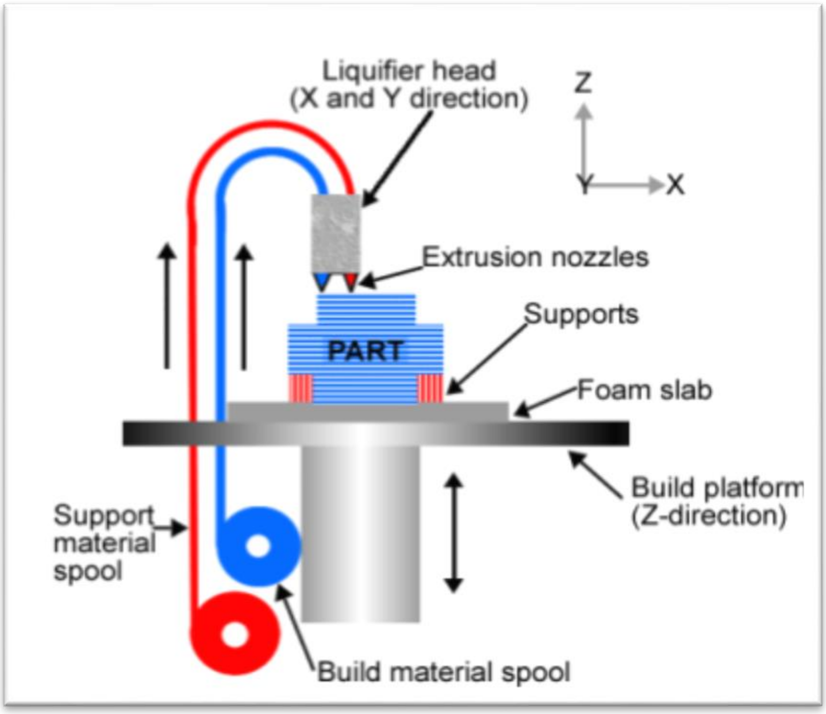


Figure 6. Fused Deposition Modelling, Dual Extrusion Scheme (Sidambe, 2014)

2.4 MakerBot printer and its printing materials

MakerBot Industries, LLC is a desktop 3D manufacturer company whose headquarter bases in Brooklyn, New York City. Bre Pettis teamed with Zach Smith and Adam Mayer found Makerbot in January 2009. Even though Pettis sold the New York-based company to Stratasys in 2013, he continues to lead MakerBot as its CEO and hit sales of $54.2 million in the first half of 2014 (Welch, 2014). As Makerbot was at its exponential growth, Thingiverse, a shared community started by Smith and Pettis in October 2008, became one of the biggest 3D learning community in the digital world (West & Kuk, 2016). Thingiverse kept growing and experienced an "explosion of uploaded and published 3D designs" by June 2013 (Howard, 2013).

As a result, Makerbot printers attracted not only keen engineers, hobbyists, but also educational organizations such as high schools and universities. At the premises of Arcada University of Applied Sciences, two models of the MakerBot Replicator + 5th Generation printer are provided, together with its printing material, PLA. In January 2014, MakerBot Replicator+ 5th Generation printer was launched with the Replicator Mini, and the Replicator Z18. These products are the latest models, which were available after Makerbot merged with Stratasys. These models all use PLA as its printing materials, and the minimum layer resolution can be 0.10 mm. (West & Kuk, 2016)

Since the MakerBot Replicator+ 5th Generation is a FDM printer, single nozzle head, the Replicator only prints in one color unless users swap the filament mid-print. The new printing bed is removable and flexible, allows users to get the objects off easily. Moreover, the printing bed also has larger size (compare to the previous MakerBot Replicator), which dimension is 252 x 199 x 150 mm (MakerBot, 2017).

The Replicator+ uses PLA (polylactide) filament, which is a biodegradable and thermoplastic, derived from starch, such as cornstarch. According to forum 3D Hubs, among exist FDM printing plastics, such as PLA, ABS, PET, Nylon, TPU (flexible) and PC, each materials has its own strength and weakness, which illustrates in ***Figure 7***. According to Figure 7, PLA is the easiest material to print, and provide a good appearance. Even it is a rigid material, but it is still breakable (3D Matter, N/A). Besides these characteristics, studies showed that PLA releases fewer potential hazard fume compare to others materials (Azimi, et al., 2016). Therefore, PLA becomes the first alternative material for household, educational environmental.

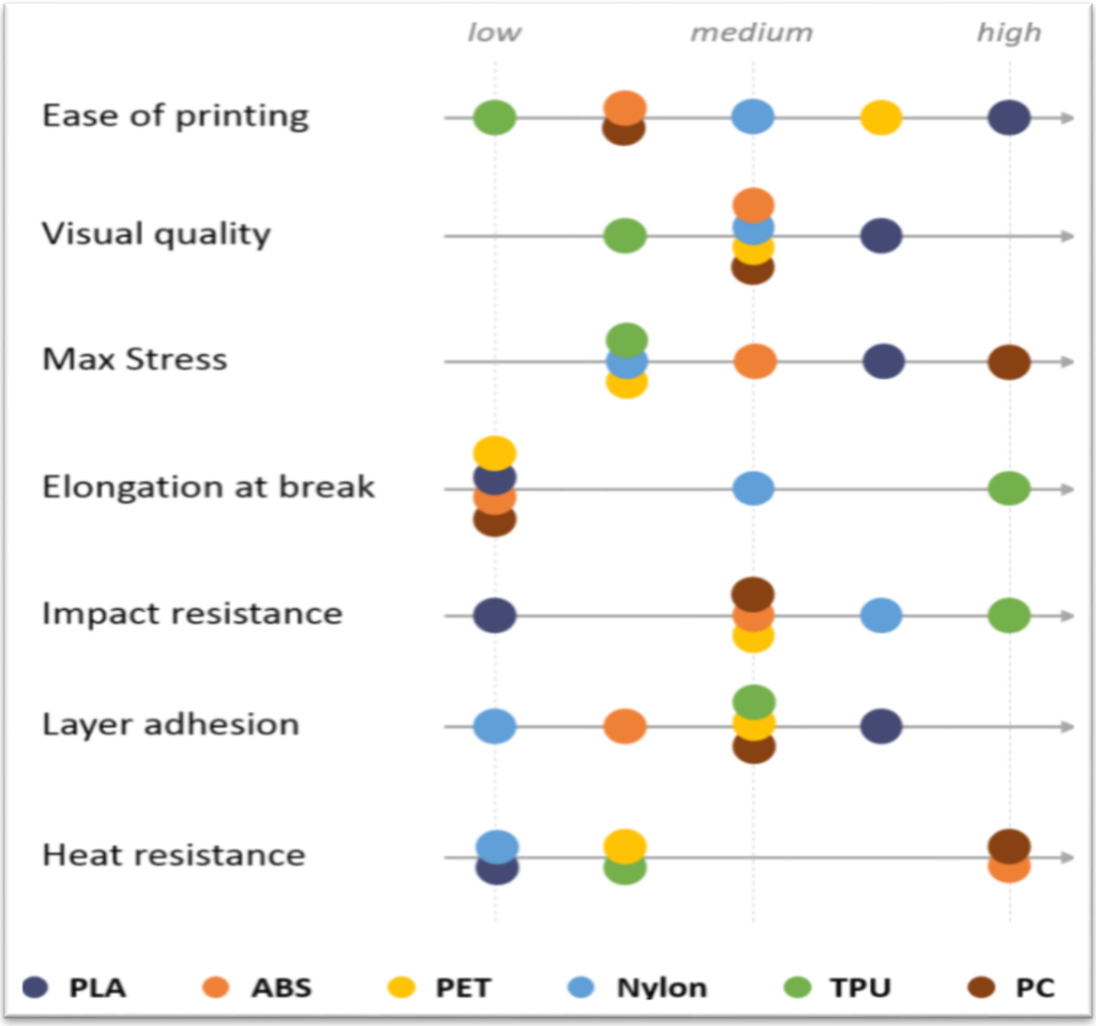


Figure 7. Research results for six polymers, Optimatter. *(3D Matter, N/A)*

2.5 Analysis Tools – SWOT analysis and Analytic Hierarchy Process (AHP)

In order to gain a better insight on two software, SWOT analysis (stand for Strength, Weakness, Opportunities, and Threat) and multi-criteria AHP were employed as analysis tools. The SWOT analysis is commonly used in strategy analysis, especially in business. Based on internal and external factors impact on an environment, SWOT analysis is a tool for environmental analysis. The SWOT analysis can be illustrated as a 2 x 2 matrix in **Figure 8**. Even though the SWOT strategy is well known for its simplicity and flexibility, the limitation in using SWOT is noticeable such as the lack of inadequate definition of factors, the lack of prioritization of factors, or the compiler bias (David W. Pickton, 1998).

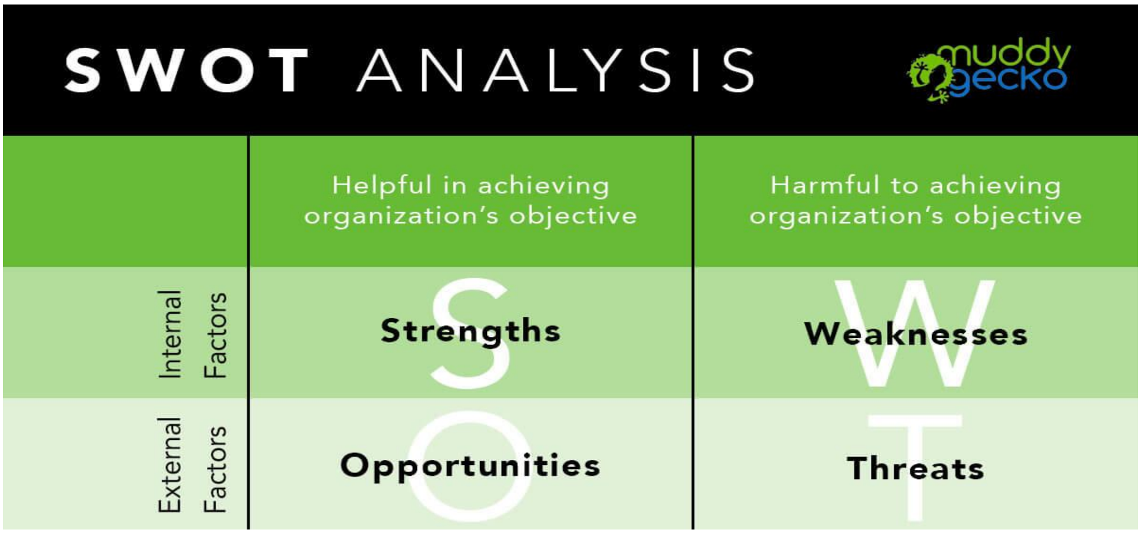


Figure 8. A SWOT analysis with its four factors in 2 x 2 matrix *(Forbes, N/A)*

In addition to SWOT analysis, Analytic Hierarchy Process (AHP) is the analysis tool that can evaluate and compare multi-criteria in a structure. The AHP model is a method that deriving ratio scales from paired comparisons to help user make decision in a way that is more rational, transparent and understandable. As a result, AHP is commonly use to evaluate intangible and psychological criteria for practical problem. The strategy to conduct AHP model can follow five steps as below:

- Identify the objective
- Structure elements in criteria, sub-criteria, alternatives, etc.
- Make a pairwise comparison of elements in each group
- Calculate the weighting and consistency ratio
- Evaluate the alternatives according to weighting

To have a clear understanding of AHP, R. W. Saaty (Saaty, 1987) presented an example of the decision on how to choose the best university. The objective is to choose the best university based on four criteria: Location, Ambience, Reputation, and Academics. The alternatives include Swarthmore College, Northwestern University, University of Michigan, Vanderbilt University and Carnegie-Mellon University.

According to Saaty, a matrix of pairwise comparison of the schools was set up. Note that this matrix is inconsistent. The consistency ratio (C.R) has a value of 0.092. If the consistency ratio exceeds 0.10, one must re-examine the judgement. After calculating the weighting based on the matrices, the result presented that Northwestern was the most suitable school with the final priority of 0.387. The hierarchy of this example was illustrated as below.

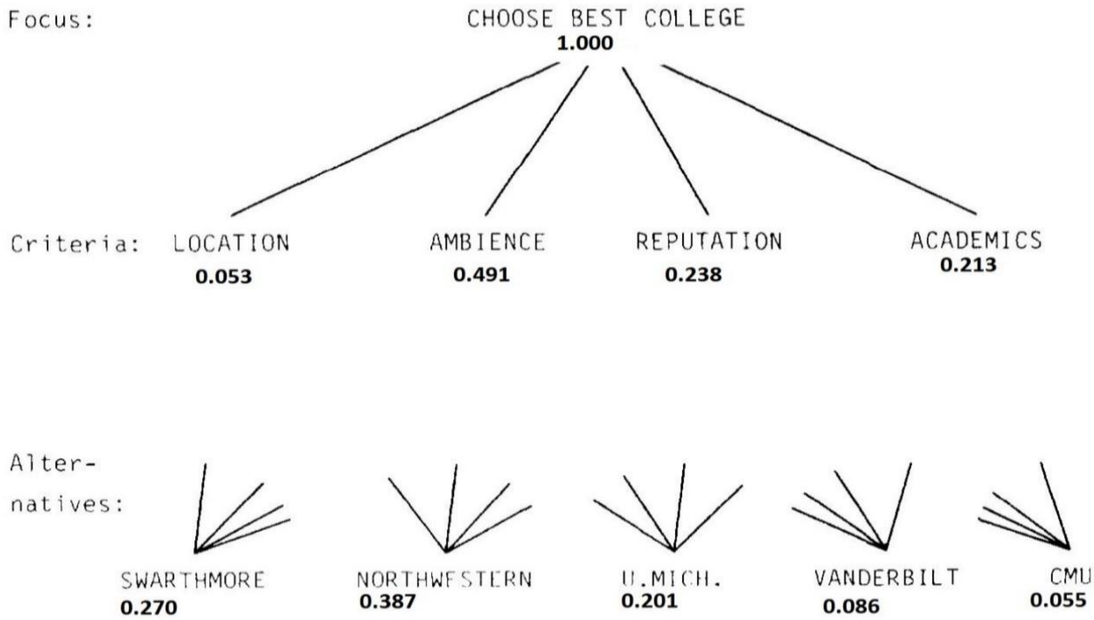


Figure 9. Hierarchy of choosing college *(Saaty, 1987)*

The principal of AHP tool is to generate a score for each criterion according to the decision maker by making pairwise comparison of the criteria. The way to fill in the matrix of comparison is rating which criterion is more important than another one, and how much more important. The fundamental scale values were presented in the table below.

Table 1. The fundamental scale *(Saaty, 1987)*

Intensity of important on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgments strongly favor one activity over another

5	Essential or strong importance	Experience and judgments strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

As Saaty stated in the explanation (Saaty, 1987, p. 164), the AHP starts by creating a matrix of pairwise comparison of the criteria that is called matrix A with the respect to the overall criteria:

Table 2. A pairwise comparison matrix A

Criteria	**Location**	**Ambience**	**Reputation**	**Academics**
Location	1	1/7	1/5	1/5
Ambience	7	1	2	3
Reputation	5	1/2	1	1
Academics	5	1/3	1	1
Sum column	18	2	4.2	5.2

In this matrix, the first comparison is Location and Ambience. The participant preferred strongly Ambience (7 times) to Location. Hence, the value 1/7 is entered in the position (1, 2) and the value 7 is entered in the position (2,1).

When a matrix of order n (n: the number of criteria) is consistent, the principal eigenvalue (λ_{max}) is equal to n value or $\lambda_{max} = n$. When the matrix is inconsistent, the principal eigenvalue (λ_{max}) exceeds n value, (Saaty, 1987, p. 170), thus we have $\lambda_{max} \geq n$. This means $\lambda_{max} - n$ is an index of departure from the consistency. Hence, the consistency index (C.I) of a matrix of comparison is given by equation of the consistency index C.I

$$C.I = \frac{\lambda_{max} - n}{n-1} \text{ (Saaty, 1987, p. 171)}$$

λ_{max}: the principal eigenvalue

n : the number of criteria

C.I : the consistency index

Additionally, the random index, R.I, is an average random consistency index derived from a sample of size 500 of a randomly reciprocal matrix using the scale 1/9, 1/8..., 1, …, 8, 9 to see if the R.I is 0.10 or less (Saaty, 1987, p. 171). The values of R.I for small criteria are shown as below:

n	1	2	3	4	5	6	7	8	9	10
R.I	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.19

The consistency ratio (C.R) is forming by comparing the consistency index and the random index:

$$0.01 < C.R = \frac{CI}{RI} < 0.1$$

C.R : consistency ratio

C.I : the consistency index

R.I : an average random consistency index

If the C.R value exceeds 0.10, the participant must revise the judgment for there may be irrational pairwise comparison. Because on a scale from 0 to 1, inconsistency should be in the range from 0.01 to 0.10, otherwise this is an error in the measurement of consistency (Saaty, 1987, p. 172). In the pairwise comparison matrix A, we normalize the matrix by divide each element in every column by the sum of that column.

For example, in the position (Location, Location), the participant rated with the value 1, and we have the sum column is 18. Thus, we can calculate the value in the position (Location, Location) as follow:

(Location, Location) = 1 ÷ 18 = 0.05556

Similar to the calculation above, we obtain the normalize value in the position (Ambience, Location) = 7 ÷ 18 = 0.38889

We follow this method to have a new matrix as below:

Table 3. Normalize the pairwise comparison, matrix B

Criteria	Location	Ambience	Reputation	Academics	Average row
Location	0.05556	0.07143	0.04762	0.03846	0.053
Ambience	0.38889	0.50602	0.47619	0.57692	0.491
Reputation	0.27778	0.25301	0.23810	0.19231	0.238
Academics	0.27778	0.16867	0.23810	0.19231	0.213
Sum column	1	1	1	1	1

By calculate the average of each row, we obtain the criteria weight or the vector of relative weight ***w***:

(Location, Ambience, Reputation, Academics) = (0.053, 0.491, 0.238, 0.213)

To check the consistency ratio, C.R, we need to determine the weight sum vector $\boldsymbol{w_s}$ by multiplying the A matrix with the vector of relative weight ***w*.** Thus, we have the formula:

$$|\mathbf{A}| \,.\, \boldsymbol{w} = \boldsymbol{w_s}$$

| A | : pairwise comparison matrix A

w : vector of relative weight

$\boldsymbol{w_s}$: weight sum vector

By applying dot product method, we obtain the weight sum vector $\boldsymbol{w_s}$**:**

$$\begin{pmatrix} 1 & 1/7 & 1/5 & 1/5 \\ 7 & 1 & 2 & 3 \\ 5 & 1/2 & 1 & 1 \\ 5 & 1/3 & 1 & 1 \end{pmatrix} \begin{pmatrix} 0.053 \\ 0.491 \\ 0.238 \\ 0.213 \end{pmatrix} = \begin{pmatrix} 0.214 \\ 1.999 \\ 0.970 \\ 0.889 \end{pmatrix}$$

However, we want to know how good the principal eigenvector estimate ***w*** is. We find the consistency vector **λ** by multiplying the weight sum vector $\boldsymbol{w_s}$ with the inverse of the vector of relative weight ***w***. Hence, we have the formula:

$$\lambda = \boldsymbol{w_s} \cdot \frac{\mathbf{1}}{\boldsymbol{w}}$$

$$\begin{pmatrix}0.214\\1.999\\0.970\\0.889\end{pmatrix}\begin{pmatrix}1/0.053\\1/0.491\\1/0.238\\1/0.213\end{pmatrix}=\begin{pmatrix}4.019\\4.105\\4.038\\4.056\end{pmatrix}$$

We adopt the average number of **λ** = (4.019 + 4.105 + 4.038 + 4.056) ÷ 4 = 4.05. We notice that if the matrix A is consistent, λ_{max} = *n* = *4*.

The C.I value can be calculated according to the equation, we obtained the value of the consistency index: C.I = $\frac{4.05-4}{4-1} = 0.0183$.

The value of R.I for a matrix 4 x 4 is 0.90. We have the consistency ratio as follow:

$$C.R = \frac{C.I}{R.I} = \frac{0.0183}{0.90} = 0.02$$

As the C.R value is in the range 0.01 < C.R = 0.02 < 0.10, the pairwise comparison matrix A is consistent.

Similar to the pairwise comparison of criteria, Saaty set up a matrix of paired comparison for the alternatives with the respect to the criteria Location, the matrix C.

Table 4. The pairwise comparison for the alternatives, matrix C

Location	**SWARTH**	**NORTHW**	**U.MICH**	**VANDERB**	**CMU**
SWARTH	1	1/4	1/3	1/3	7
NORTHW	4	1	2	3	7
U.MICH	3	1/2	1	3	6
VANDERB	3	1/3	1/3	1	4
CMU	1/7	1/7	1/6	1/4	1

Following the similar calculation, we normalize the matrix C by divide each element in every column by the sum of that column. Thus, we obtained the vector of relative weights for the criteria (1) Location, the weights are listed as below:

(SWARTH, NORTHW, U.MICH, VANDERB, CMU) = (0.115, 0.402, 0.283, 0.163, 0.037)*

*Note that the value in this vector of relative weight regards to the criterion Location is a round-up number from the software package supporting AHP, called Expert Choice, for the IBM PC, which is slightly different from the value of hand-calculation. However, we accepted these round-up numbers in order to have an easy understanding for readers. To readers whom need to have further understanding and calculations that are more accurate can follow the Appendix enclosed.

With the value of C.R = 0.092 (Saaty, 1987, p. 165), the matrix C is consistent. Similar to the criteria (1) Location, Saaty gave the local derived scales for other criteria (Saaty, 1987, p. 165): (2) Ambience, (3) Reputation, (4) Academics

(2) (SWARTH, NORTHW, U.MICH, VANDERB, CMU) = (0.034, 0.539, 0.250, 0.121, 0.056)
(3) (SWARTH, NORTHW, U.MICH, VANDERB, CMU) = (0.521, 0.235, 0.147, 0.038, 0.059)
(4) (SWARTH, NORTHW, U.MICH, VANDERB, CMU) = (0.564, 0.209, 0.132, 0.040, 0.055)

Thus, we have the final rating matrix for all alternatives. We multiple the final rating matrix with the vector of relative weight for all the criteria - vector ***w,*** in order to find the final priority among these alternatives:

$$\begin{pmatrix} 0.115 & 0.034 & 0.521 & 0.564 \\ 0.402 & 0.539 & 0.235 & 0.209 \\ 0.284 & 0.250 & 0.147 & 0.132 \\ 0.163 & 0.121 & 0.038 & 0.040 \\ 0.037 & 0.056 & 0.059 & 0.055 \end{pmatrix} \begin{pmatrix} 0.053 \\ 0.491 \\ 0.238 \\ 0.213 \end{pmatrix} = \begin{pmatrix} 0.270 \\ 0.387 \\ 0.201 \\ 0.086 \\ 0.055 \end{pmatrix}$$

By applying dot product method, we obtained these values as follow:

SWARTH = (0.115 x 0.053) + (0.034 x 0.491) + (0.521 x 0.238) + (0.564 x 0.213) = 0.270

NORTHW = (0.402 x 0.053) + (0.539 x 0.387) + (0.235 x 0.238) + (0.209 x 0.213) = 0.387

U.MICH = (0.284 x 0.053) + (0.250 x 0.491) + (0.147 x 0.238) + (0.132 x 0.213) = 0.201

VANDERB = (0.163 x 0.053) + (0.121 x 0.491) + (0.038 x 0.238) + (0.040 x 0.213) = 0.086

CMU = (0.037 x 0.053) + (0.056 x 0.491) + (0.059 x 0.238) + (0.055 x 0.213) = 0.055

After weighting the final rating matrix, we obtained the global derived scale. This showed the final priority NORTHW or Northwestern University with 0.387 is the most preferred university. Swarthmore College takes the second place with a priority of 0.270.

In our study, the main goal is to compare SolidWorks and Onshape, in order to find a functional software for engineering design. To support the calculation in AHP multi-criteria model, a free web based AHP solution – AHP Online System (Goepel, 2017) was employed to assist the calculation. According to Saaty (Saaty, 1987), the assessment includes two types of comparison: the relative evaluation and the absolute evaluation. The relative evaluation would present the priorities of the criteria that are set in advance independently of any alternatives. After conducting the relative evaluation, the absolute evaluation is applied to rate the alternatives regarding the criteria or the intensities of the criteria. By checking off the rating of each criterion and summing these rating for all the criteria, each alternatives are scored. This process would produce a ratio scale score for the alternatives. During the whole process, participants need to check the CR less than 10%. If the CR is higher than 10%, the website will highlight and offer suggestion to maintain a CR that is less or equal to 10%.

Since the AHP Online System can automatically calculate the ratio score based on the priorities ranking, participants will rate each criterion based on their personal priorities. Note that the priorities ranking would be different because of different perspectives.

3 METHOD

The aim of this study is to assess the capacity of two software in modelling, assembly and stress analysis. The approach to assess two software is to design a box with hinge, include two parts: top and bottom, and a pin. In order to assembly two parts, an insert mate relationship will be introduced between two parts and a pin. The idea of the box design came to the author after watching a case study on Lynda.com online course, Design for Additive Manufacturing: FDM by Kacie Hultgren (Hultgren, 2018).

The methodology employed the SolidWorks education version 2018, free of charge for students that are qualified for SolidWorks licenses. This education version will expire within a year. The Onshape service is the Onshape Education plan, free for students and educators. This package has access to unlimited storage.

3.1 Design using SolidWorks

There are three main steps to create the object: model a box, extrude a hinge, and assembly modelling. From the origin, a square with dimension 70 x 70 mm was sketched on the Top plane (See **Figure 13,** Left picture). The sketch was extruded with 30 mm depth of extrusion.

The Extrude feature generate a solid object. To obtain a hollow box with 1 mm wall thickness, the author uses the Shell features, Multi-thickness setting applied on multiple faces (6 faces of the box), with Shell thickness: 1 mm. (see **Figure 10**)

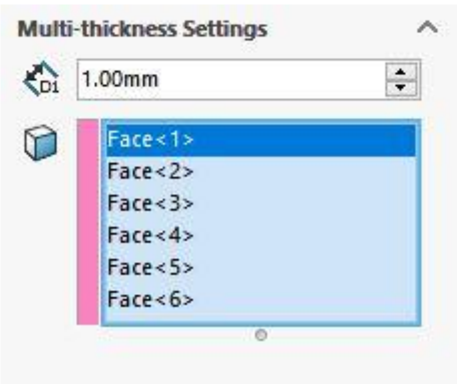


Figure 10. Setting of Shell feature

The next step is create a Split line for the Split body. The author decided to choose a new plane that has an offset distance 15 mm to the Top plane. (See **Figure 11)**

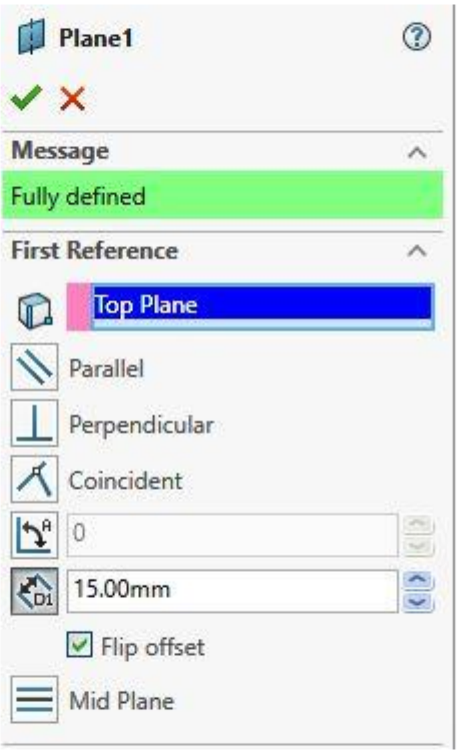


Figure 11. Split plane setting

Next, to separate two parts from the existing box, the Split feature was applied by clicking on Feature toolbar: **Insert**, **Feature**, and **Split**. When splitting a body, under the **Resulting Bodies**, user can select the bodies to save or click **Auto-assign Names**. User can change name or SolidWorks automatically names all the bodies.

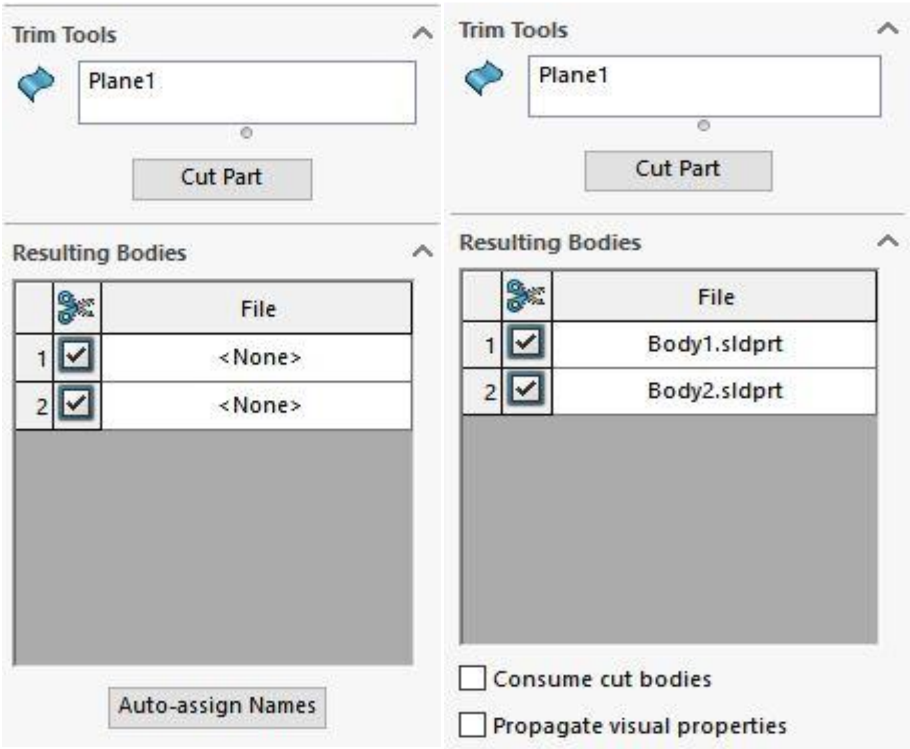


Figure 12. Split body and save parts

(Left: before Auto-assign bodies, Right: After Auto-assign names and save parts)

After splitting, each part has the same dimension of 70 x 70 x 15 mm.

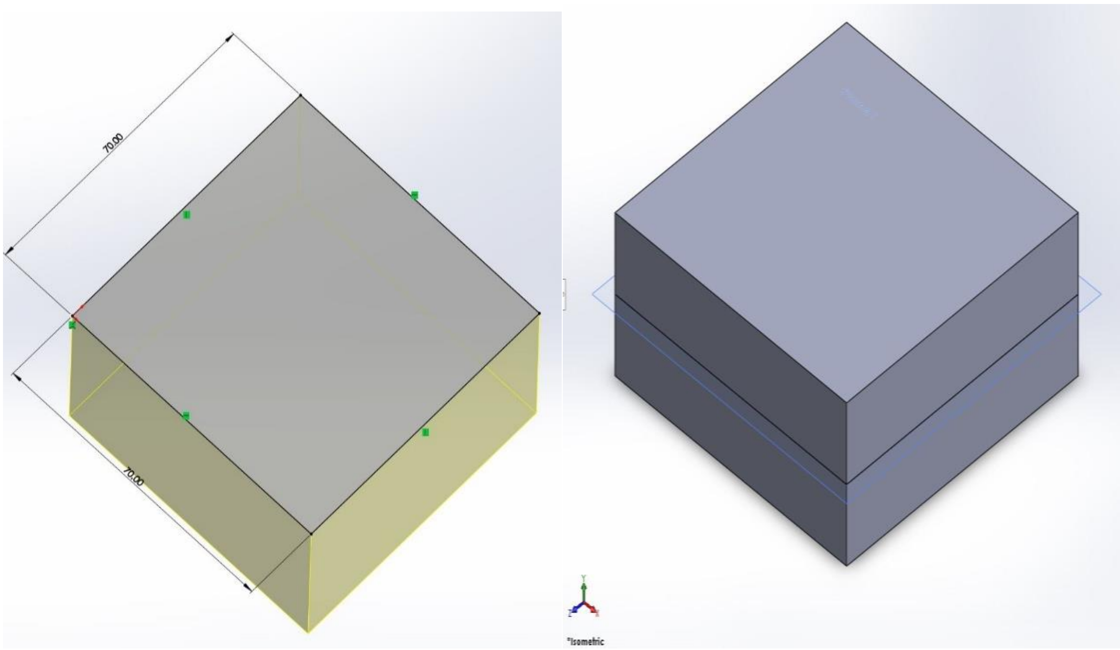


Figure 13. Modelling a box (SolidWorks)

(Left: Main sketch, Right: The box was split into two parts)

Since the **Split** feature divided the box into two parts and saved each part as a separate entity, the hinge was sketched and extruded on each entity. A pin was modelling with a dimension of 70 mm length and diameter of 1.2 mm.

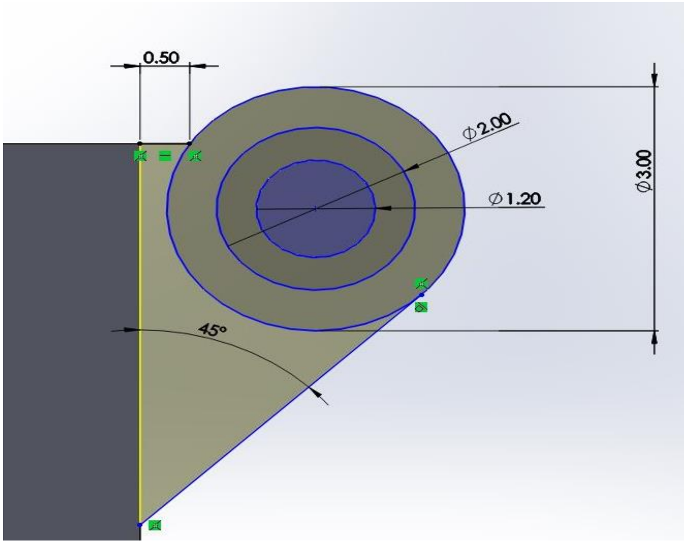


Figure 14. Sketching the hinge (SolidWorks)

In order to rotate around the pin, the hinge needs the knuckles. The new plane was created that is coincident to the open face of the box. A sketch of the knuckles was sketch on this new plane, and then was removed by **Cut-Extrude** feature.

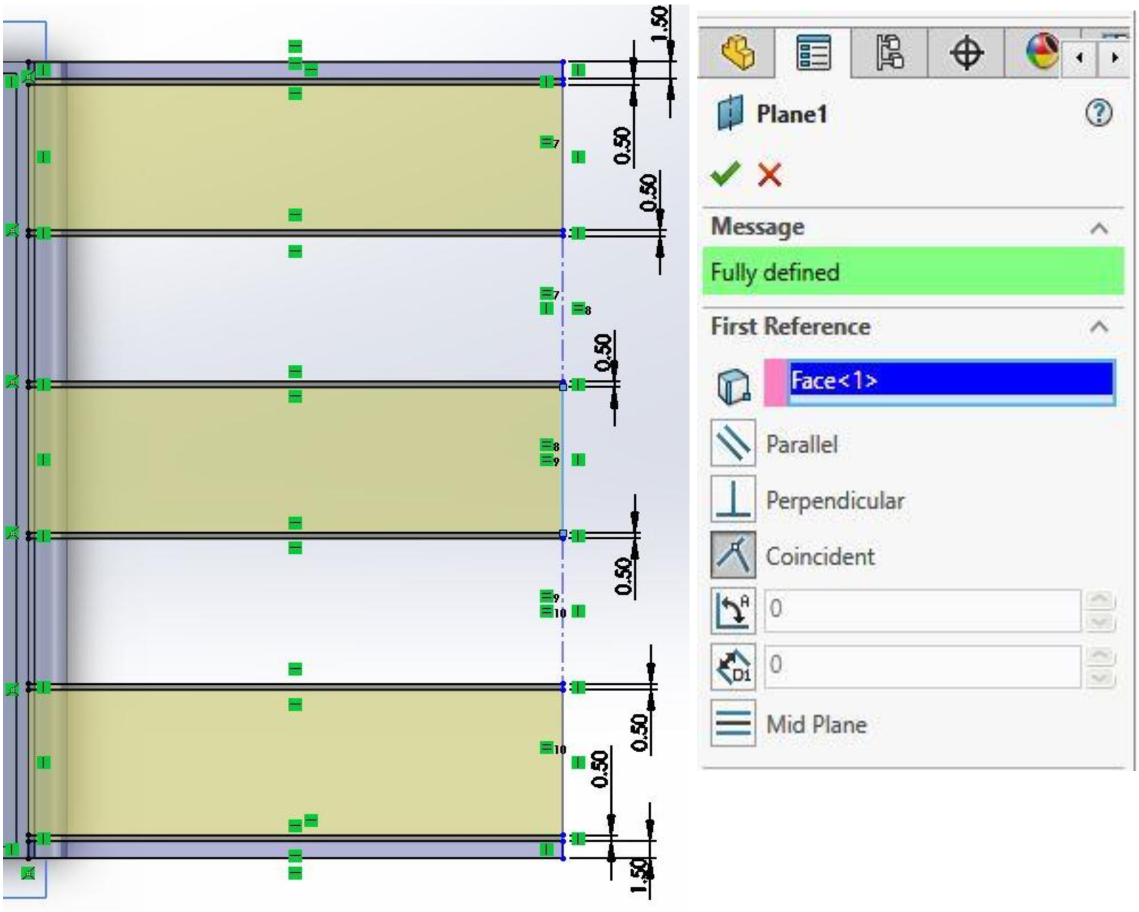


Figure 15. Sketching and modelling knuckles

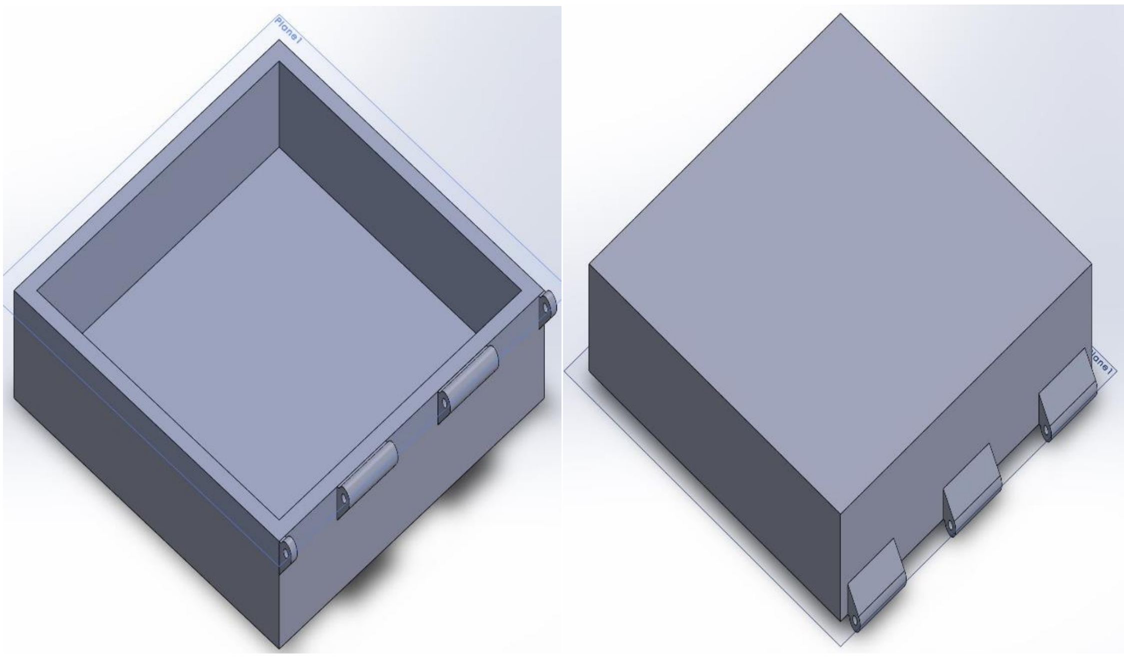


Figure 16. Two parts with hinge (SolidWorks)

(Left: Bottom part, Right: Top part)

To keep two parts to move along the common axis (Z-axis) and cannot pull apart, a concentric mate was applied on the faces of the knuckle on the top hinge and bottom hinge. The concentric mate was introduced to the pin and the hinge, in order to minimize the slack between two parts. A distance between the side faces of the knuckles was set at 0.5 mm.

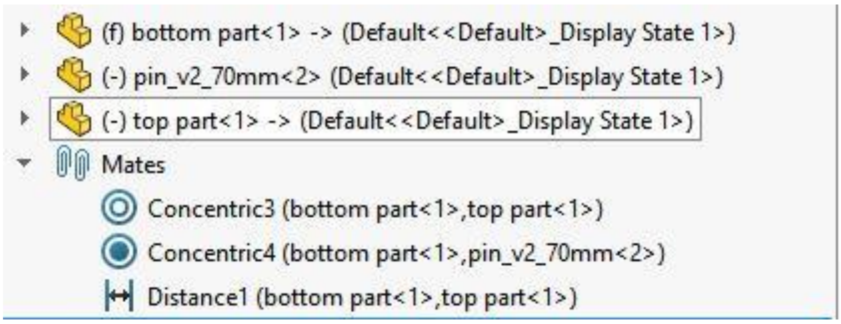


Figure 17. Concentric mates

Two parts can open and the hinge can rotate around 180˚. The open box with hinge was illustrated as below.

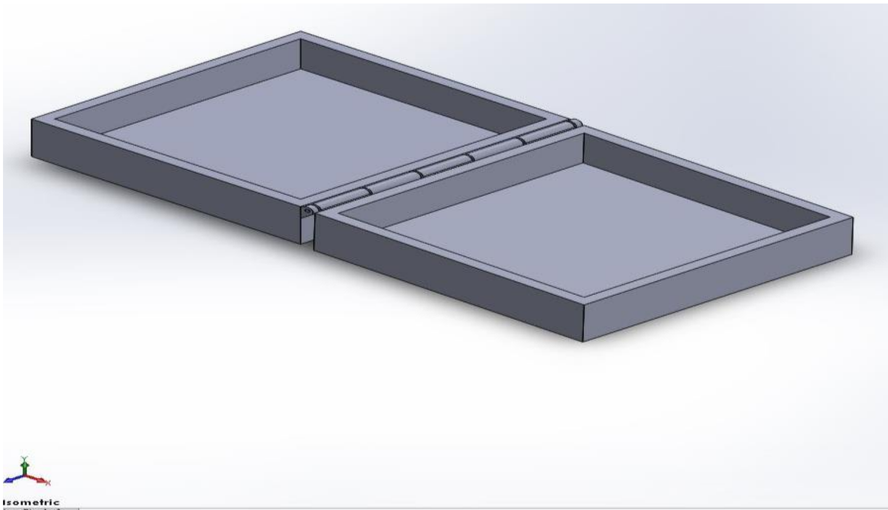


Figure 18. Assembly 2 parts and the pin

3.2 Design using Onshape

Similar to the modelling method in SolidWorks, a box was extrude from the main sketch. Onshape also shares the similar user interface with SolidWorks in its Part Studio. First, from the origin, on Top plane, a square 70 x 70 mm was sketched and extrude to 30 mm. To obtain a hollow box, users can tick **Hollow**; choose the whole object instead of choosing individual faces and input desire shell thickness.

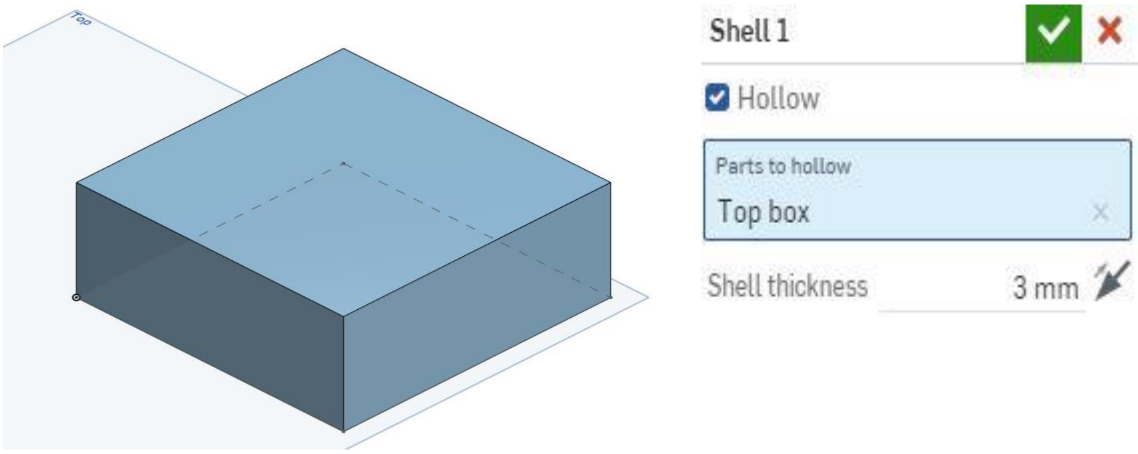


Figure 19. Extrude a box and its shell thickness

A plane with distance offset 15 mm from Top plane was created. The new plane the Split plane of the entity.

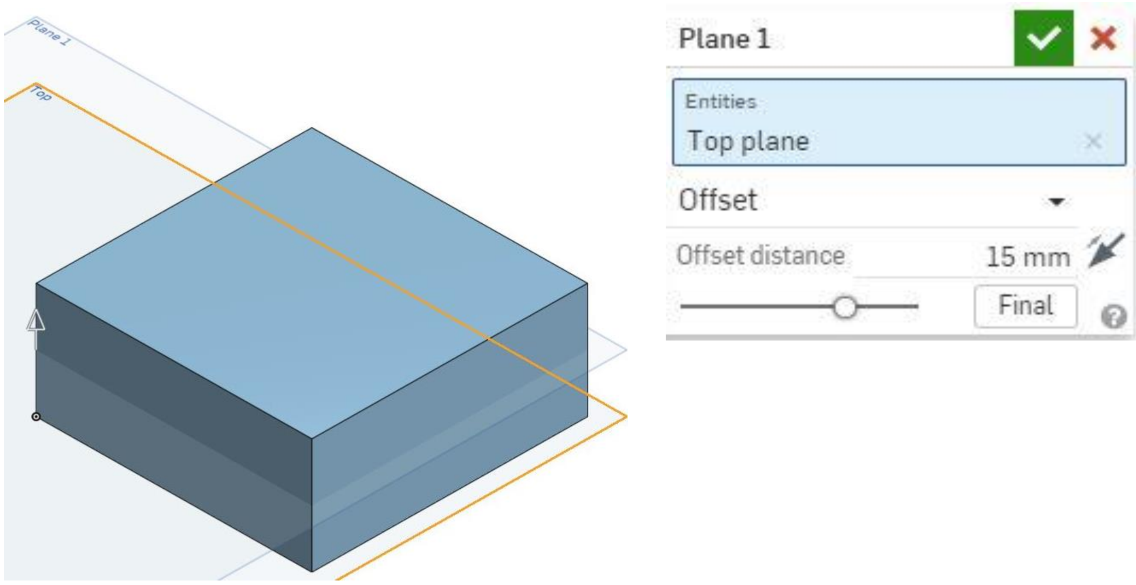


Figure 20. Split plane setting

The Split feature in Onshape functions the same method in SolidWorks: split the entity into multi-bodies. Yet different from SolidWorks, Onshape automatically saved two separate entities in the same Part Studio after splitting the body.

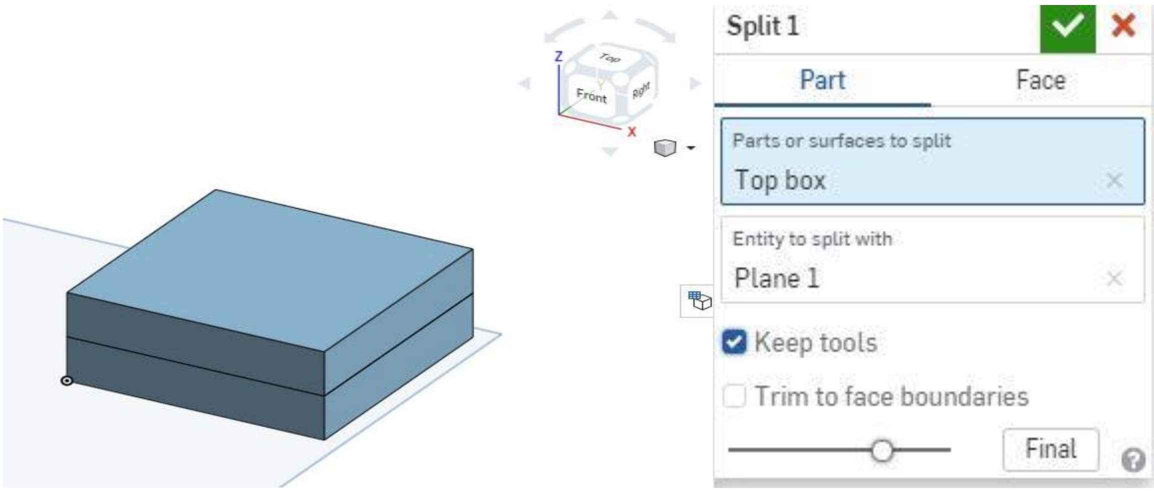


Figure 21. A split box without hinge

Since Onshape kept the split bodies in the same part studio, Onshape offers Hide function in order to create a flexible user interface. Users can turn on/off the Hide feature to have a clear view while sketching or modelling a new entity. Note that, once a sketch or an entity is hidden, it is not being deleted or removed. Users can review or edit it later.

The sketch of the hinge was on a face of bottom part, Front view of the object. Note that, the hinge was modelled as a separated part from bottom box and top box. The figure illustrated the hinge sketch as below, for further specific view, a drawing was attached in Appendix list.

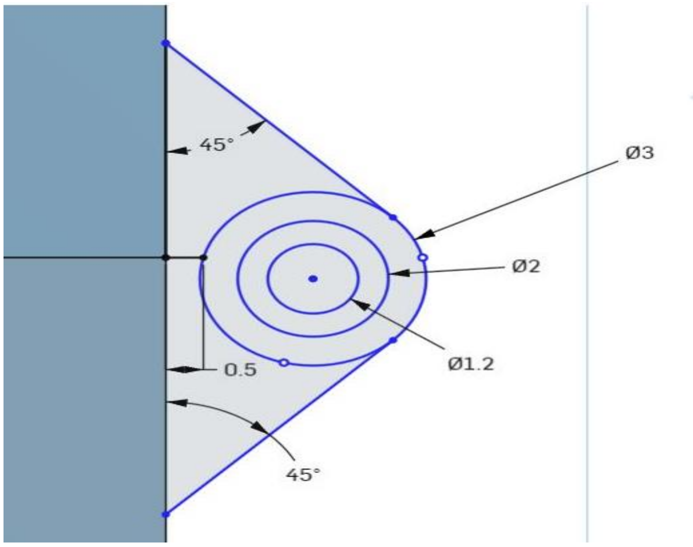


Figure 22. Sketching a hinge

The hinge was sketch on both parts and was extruded on the Y-axis 70 mm, along the length of the box. Next step is to create the knuckles, thus the hinge can rotate. On the Split plane, the author sketched the knuckles then created the gap between knuckles by click **Extrude**, **Remove**, input the gap, and set the **Depth** 25 mm. In Onshape, Extrude feature can function as create part or remove part from sketch.

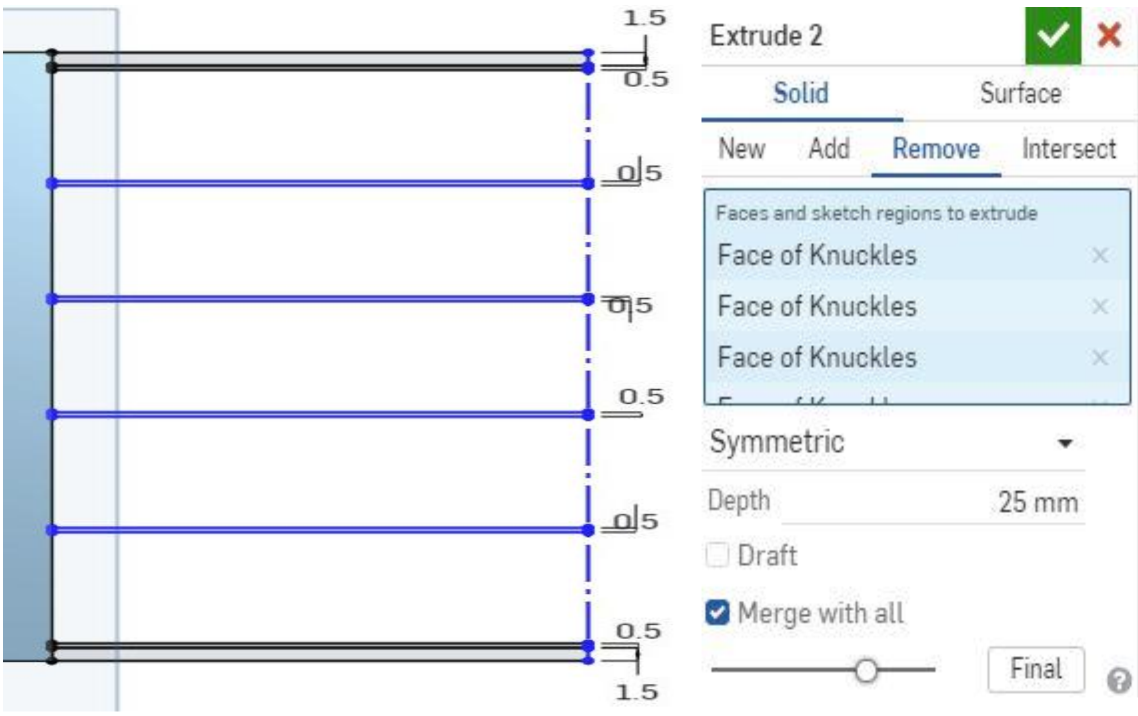


Figure 23. Sketch the gap and create knuckles

In the same Part Studio, extrude the pin from the hinge sketch. Dimension: 1.2 mm diameter, 70 mm length.

As Onshape keeps all modelling parts in the same Part Studio, users need to insert all desired entities into the Assembly tab by click **Insert**, and choose the entities.

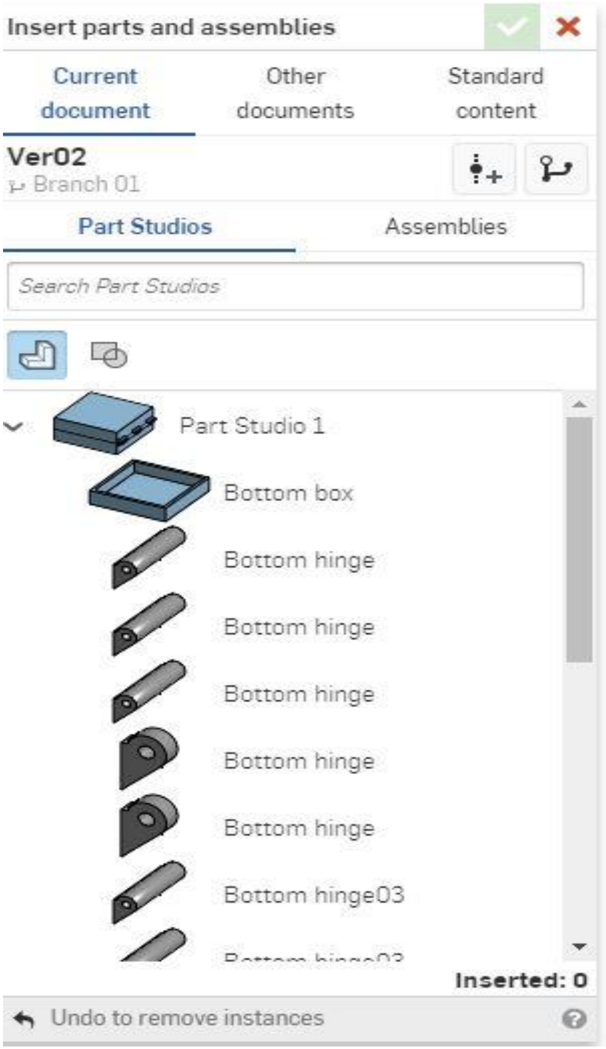


Figure 24. Inserts parts and assemblies

Because each entities are an independent items that have no specific mates to each other, these entities would move unexpectedly while assembling process. Hence, in Assembly tab, it is convenient to use **Group** feature to fix the position of selected components, which was modelled in the same Part studio. Thus, Group can keep a relative position between components without creating **Mates**.

There are two main groups in the **Mate features**: Group 1 - the bottom box, its hinge and the pin, Group 2 – the top box and its hinge.

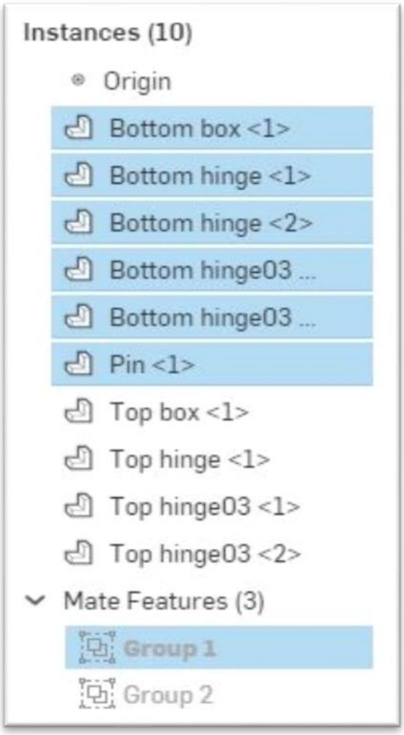


Figure 25. Group components in Mate features

Because the hinge box should be able to rotate, the **Revolute** mate was introduced to the Pin and the inside face of the knuckles.

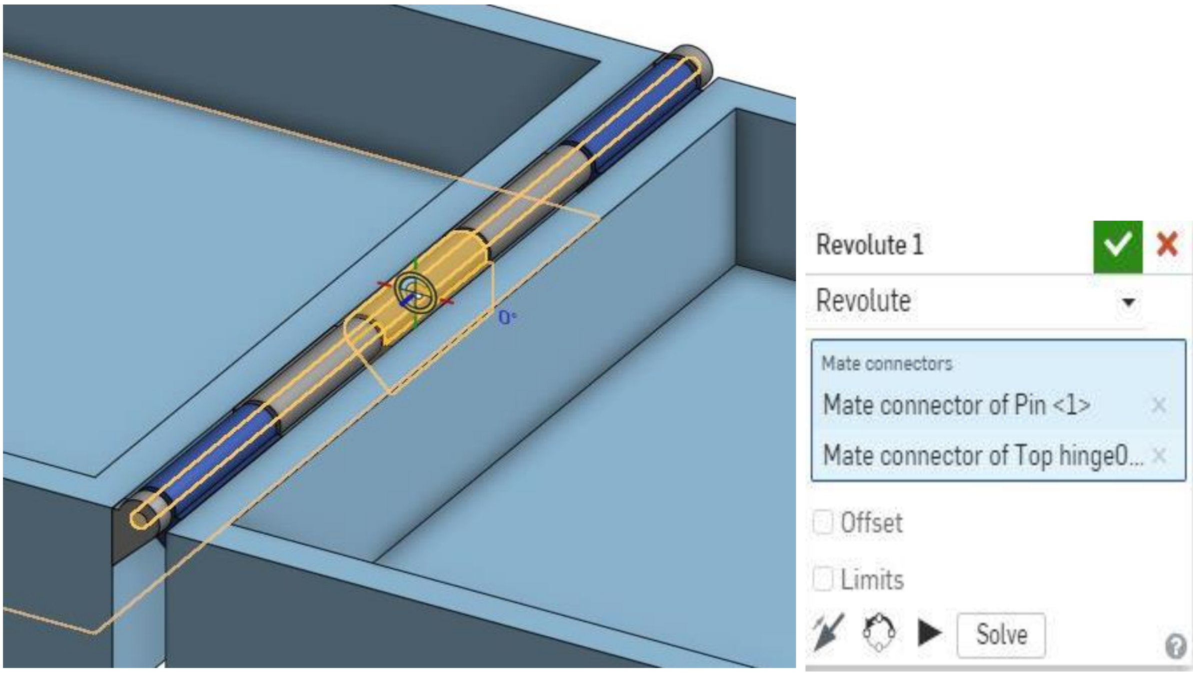


Figure 26. Revolute mate

Now two parts of the box can be rotated, the open box with the hinge was illustrated as below.

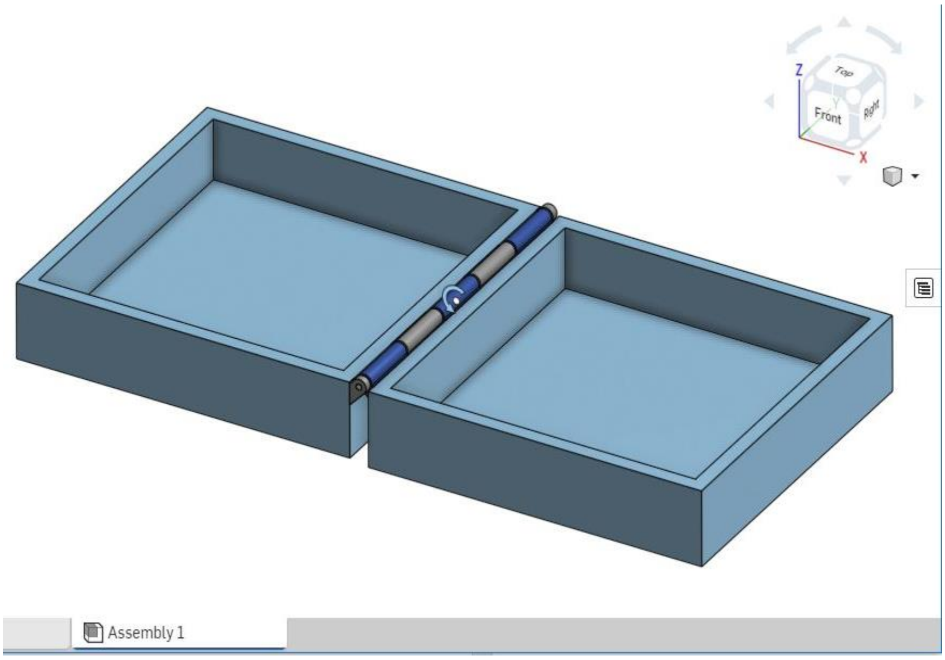


Figure 27. Assembly 2 parts

3.3 Prototyping products

Both of two designs were exported into STL file and ready for prototyping process. To export STL file from Onshape, users hold Right Mouse button, click **Export** and choose suitable file format (see **Figure 28**). Users can select different file format, units, resolution. The printing file also can exports as individual files, if exporting assembly. Onshape allows its users to export printing file directly both from Part Studio and Assembly interface.

However, to export STL file from Assembly in SolidWorks, users need to process extra step. First, users need to save the Assembly as a Multi-body part. Instead of saving the Assembly as an assembly file, users can save the file as a new Part file by clicking on **Save as;** choose **Save as type**, Part (SLDPRT) modified. This means users create a new Multi-body part from this method. In addition, we can save this Multi-body part as an STL file by converting each of components within the assembly into imported body geometry. Because SolidWorks recognizes this as separate solid bodies, it is easy to export this file as an STL file. This STL file will be ready to import to 3D slicer software such as Makerbot Print.

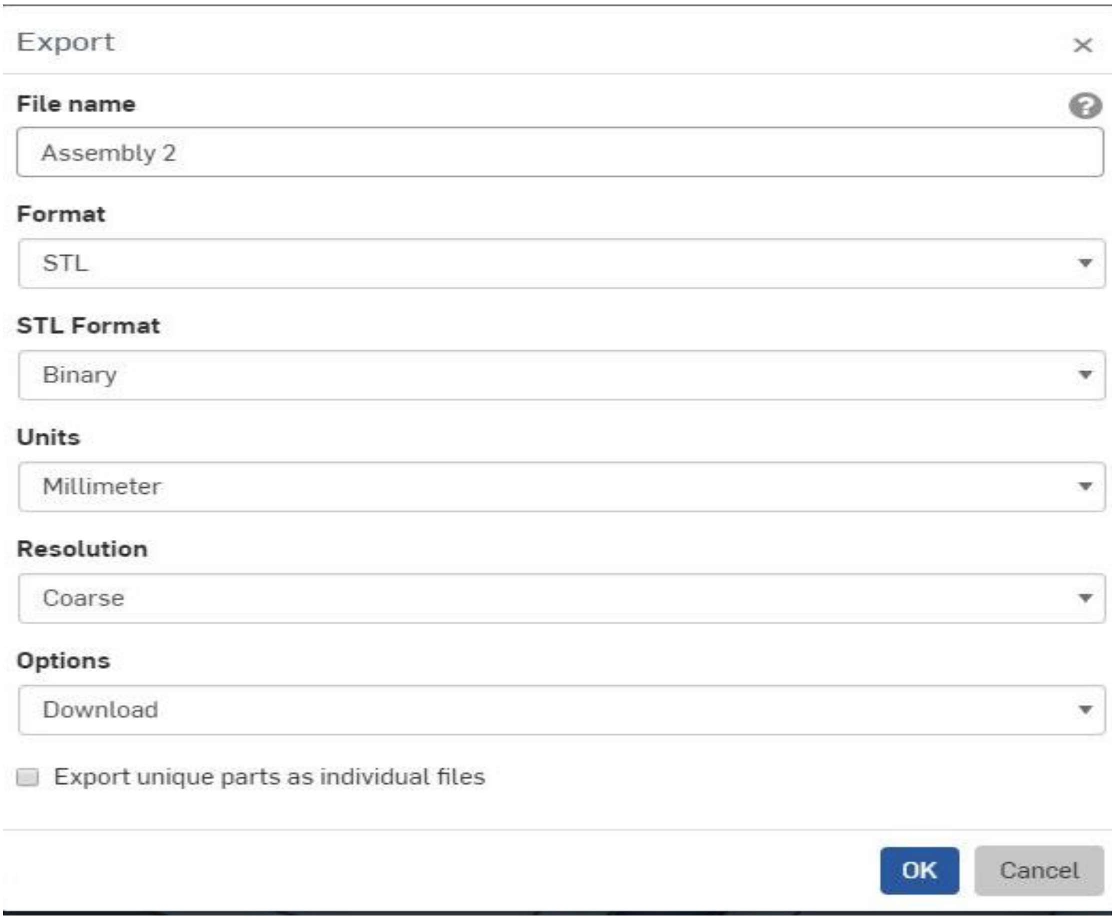


Figure 28. Export printing file in Onshape

Makerbot Print software was employed to adjust setting and execute the printing process. The rule of thumb to obtain a good appearance of printing object is to choose the best orientation for object that requires the least support or bridges. Even though the support density can be adjusted (the higher the support density, the harder to remove support material from object), the support usually leaves marks on the 3D surface. To 3D printing an open box with hinge in Makerbot Print, the setting is adjusted to obtain an aesthetic appearance and within 2 hours approximately. The setting was presented in

Table *5*.

By using the Print Preview function in Makerbot Print, the estimate printing time can be up to 4 hours 22 minutes for one model. The author decided to adjust the dimension of the original object to decrease printing time. The new dimension of the box is 30 x 70 x 16 mm (the hinge dimension is consistent between the new model and the original model).

After reducing the width and the height, the printing time for one object is 1 hour 24 minutes approximately.

Table 5. Custom setting in Makerbot Print

Raft	Turn On	The raft will keep object stable on the printing plate
Layer Height	0.2 mm	
Infill Density	15%	Increasing density will increase printing time
Infill Pattern	Diamond fast	This pattern saves printing time
Number of shell	2 shells	
Support	Turn On	
Support Angle	45˚	The hinge needs a support to avoid sagging
Support Density	10%	The smaller the density, the easier to remove support material in post processing

4 RESULTS

4.1 Program reviewing

4.1.1 SolidWorks

STRENGTHS **(internal factors, positive points)**	**WEAKNESSES** **(internal factors, negative points)**
• Professional parametric modelling software • One of the most dominant mechanical CAD software in industrial scale • SolidWorks is used widely in engineering simulation • Offer professional simulation package for engineering simulation (FEA, CFD, etc.) • Essential tutorials for beginners can be found within the software or from the Resource center website	• The license fee is significantly high, especially the cost of professional premium package is prohibitive ($7,995) (Cohn, 2018) • Require intensive hardware system that is compatible with the software • Features in modelling and simulation are excessive for hobbyist and non-professional users • Data management is costly and inflexible, lack of supporting multi-user modelling, undo/redo, branch/merge designs
OPORTUNITIES **(external factors, positive points)**	**THREATS** **(external factors, negative points)**
• SolidWorks academic certification is renowned for its ability to assess technical proficiency of users.	• Free, open source, parametric modelling software is available such as Onshape (cloud based) or FreeCAD • Other noticeable software that can work on non-parametric and parametric model competes with SolidWorks such as Inventor, Siemen NX, Fusion 360, etc.

4.1.2 Onshape

STRENGTHS **(internal factors, positive points)**	**WEAKNESSES** **(internal factors, negative points)**
• Professional parametric modelling software • Require no intensive hardware support, compatible with Windows and Mac OS • Free of charge for education package, able to access by any browsers, update frequently, no version conflict • Available interactive tutorials and Webinar • Free and flexible data management, support multi-users modelling, branch/merge designs, undo/redo	• A new service yet similar interface with SolidWorks • Onshape does not offer engineer simulation; simulations carry by Add-in service such Simscale that may increase additional cost for users. • Technical drawing in Onshape Drawing is not fully industrial standard. It is not an ideal solution for beginners to learn mechanical drawing. • Require a stable internet bandwidth, especially when loading/working on a complicated part.
OPORTUNITIES **(external factors, positive points)**	**THREATS** **(external factors, negative points)**
• Strong community support from users • Informative forum assists beginners, keen hobbyist to learn and proficient in using Onshape.	• Even though Fusion 360 and SolidWorks are not fully cloud-based, these two software are highly competitive over Onshape. • Fully cloud-based is a completely new interface, which requires more time to improve and get adapted from users.

4.1.3 AHP model

The methodology of AHP model is to rate how importance one criteria over others by making pairwise comparison. The rating scale is 1 - 9, in which, 1 – Equal Important, 3 –

Moderate Importance, 5 – Strong Importance, 7 – Very Strong Importance, 9 – Extreme Important. The main criteria include Education, Features, Accessibility, and Simulation. The sub-criteria Feature include Part Modelling, Assembly Modelling, and Drawings. The Accessibility criteria contains sub-criteria such as IT admin, Data Management, and Sharing CAD data (between users). There is no comparison in price because costs and benefit comparison can be conducted later. The AHP model was illustrated as below.

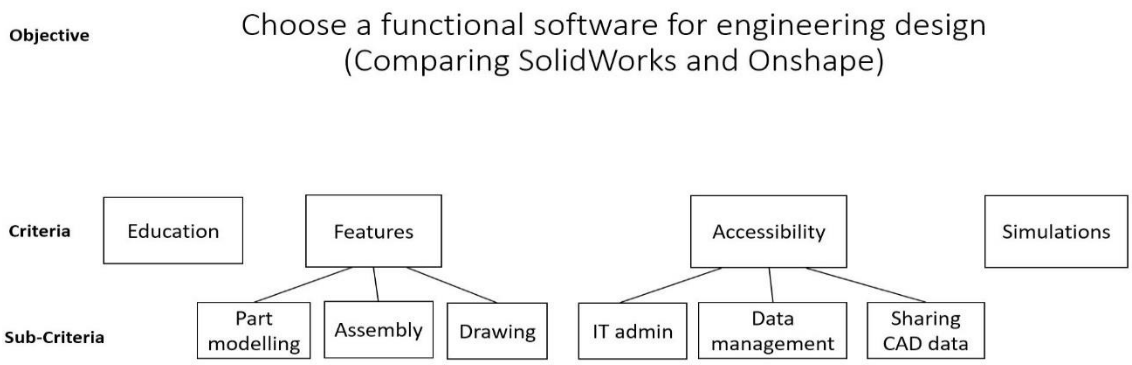
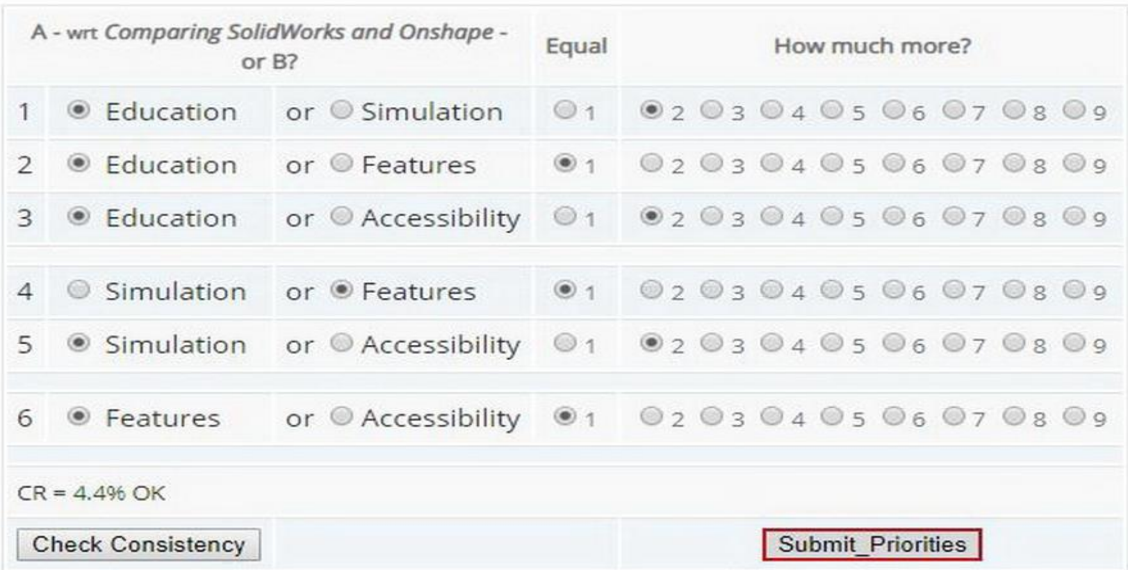


Figure 29. Hierarchy of comparing SolidWorks and Onshape

To gather the data for the assessment, participants will rate main criteria first, then evaluate how importance each sub-criteria over others in the same group criteria. In our case, the group assessment of the main criteria that was analyzed by the AHP solution website could be represented in **Figure 30**.



A - wrt *Comparing SolidWorks and Onshape* - or B?				Equal	How much more?
1	● Education	or	○ Simulation	○ 1	● 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
2	● Education	or	○ Features	● 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
3	● Education	or	○ Accessibility	○ 1	● 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
4	○ Simulation	or	● Features	● 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
5	● Simulation	or	○ Accessibility	○ 1	● 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
6	● Features	or	○ Accessibility	● 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
CR = 4.4% OK					
Check Consistency					Submit_Priorities

Figure 30. Pairwise comparison between main criteria

After participants input the priorities, the AHP calculator will automatically rank the criteria; present how much percentage one criterion contributes to the main goal. The ranking list shows the results based on the percentage in **Table 6**. Since each participants have different priorities, thus the ranking result would be inconsistent.

Table 6. Resulting Priorities List from AHP Online System

Criteria	Sub-criteria	Priorities	Rank
Education		34.31 %	**1**
Simulation		24.26 %	**2**
Features	**Part Modelling**	10.40 %	**2**
	Assembly	10.40 %	
	Drawing	3.47 %	
Accessibility	**IT admin**	4.46 %	**4**
	Data Management	5.62 %	
	Sharing CAD data	7.08 %	

According to the result, Education factor took the first place in the priorities list (34.3%). Meanwhile, Simulation and Features factor shared the second place in the list (both are 24.3%). The last priority is Accessibility (17.2%). This result included the ratio score of the sub-criteria, which was summing for all the criteria.

Similarly, the alternative evaluation was conducted by making pairwise comparison between Onshape and SolidWorks. The comparison between two software can be showed as below in **Table 7**. The ratio presented how much more is SolidWorks preferred over Onshape in each criteria and sub-criteria.

Table 7. Decision Hierarchy in ratio

Criteria	Sub-criteria	SolidWorks (ratio)	Onshape (ratio)
Education		0.25	0.75
Simulation		0.75	0.25
Features	**Part Modelling**	0.50	0.50
	Assembly	0.25	0.75
	Drawing	0.75	0.25
Accessibility	**IT admin**	0.3333	0.6667
	Data Management	0.1667	0.8333
	Sharing CAD data	0.1667	0.8333
Group Result		**0.4078**	**0.5922**

As the participant compared and rated each software regard to each criterion individually. To picture how important one factor is over the others, is difficult. The radar chart in **Figure 32** presented how the participant preferred a criterion to the others. Clearly, the participant deemed that Onshape has advantages in IT admin, Data Management, Sharing CAD data, Education and Assembly. Meanwhile, the participant found that SolidWorks is dominant in Simulation and Drawing.

However, the ratio result does not represent how many percentages a criterion contribute to the priorities of each software. Hence, we need to calculate the percentages according to the ratio and the total percentage of each main criteria. (The data is from ***Table 6*** and **Table 7**)

- In Education

SolidWorks: 0.25 * 34.31 % = 8.58 %

Onshape: 0.75 * 34.31 % = 25.73 %

- In Simulation

SolidWorks: 0.75 * 24.26 % = 18.165 %

Onshape: 0.25 * 24.26 % = 6.065 %

- In Features

SolidWorks: 0.5 * 10.40 % (Part Modelling) + 0.25 * 10.40 % (Assembly) + 0.75 * 3.47 % (Drawing) = 10.41 %

Onshape: 0.5 * 10.40 % (Part Modelling) + 0.75 * 10.40 % (Assembly) + 0.25 * 3.47 % (Drawing) = 13. 87 %

- In Accessibility

SolidWorks: 0.334 * 4.46 % (IT Admin) + 0.167 * 5.62 % (Data Management) + 0.167 * 7.08 % (Sharing CAD data) = 3.61 %

Onshape: 0.667 * 4.46 % (IT Admin) + 0.834 * 5.62 % (Data Management) + 0.834 * 7.08 % (Sharing CAD data) = 13.56 %

Thus, the result of the consolidated priorities can be presented in **Table 8**.

Table 8. Decision Hierarchy in percentage

Criteria	Sub-criteria	SolidWorks (%)	Onshape (%)
Education		8.58	25.74
Simulation		18.20	6.07
Features	**Part Modelling**	5.20	5.20
	Assembly	2.60	7.80
	Drawing	2.60	0.87
Accessibility	**IT admin**	1.49	2.97
	Data Management	0.94	4.68
	Sharing CAD data	1.18	5.90
Group Result		**40.78**	**59.22**

As a result, Onshape overcomes SolidWorks in general ranking, especially Onshape took the highest percentage with Education factor in the priorities list. The participant prefer Education to other factors (see **Figure 31**). Onshape was viewed as a software offer better service in Education and Accessibility. Even though Onshape and SolidWorks is competitive in Part Modelling, SolidWorks was outcomes Onshape in Assembly and Drawing. However, Onshape outperforms SolidWorks in Accessibility (includes IT admin, Data Management, and Sharing CAD data between users, see **Figure 32** and **Table 8**).

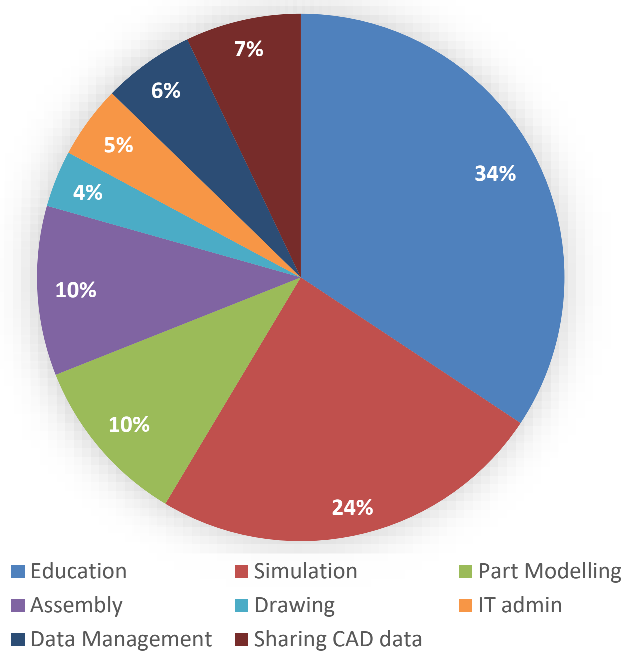


Figure 31. Priorities evaluation according to percentage

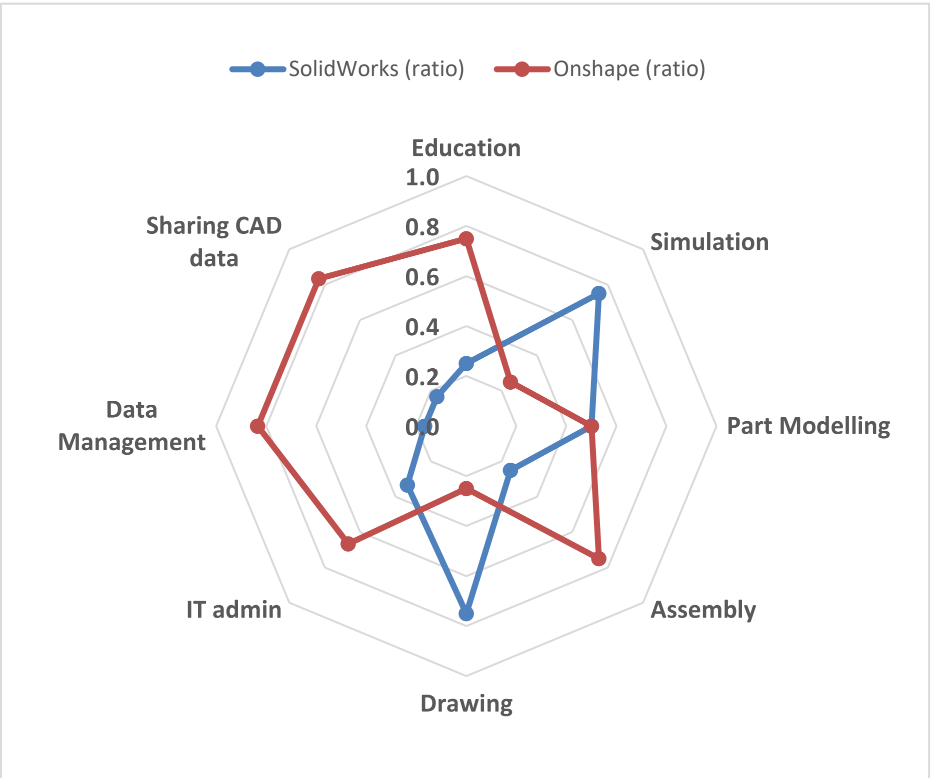


Figure 32. Alternatives evaluation according to ratio

4.2 Product reviewing

4.2.1 SolidWorks

Production information

- Object dimension (height x length x width): (± 0.2) 0 x 69.6 x 29.6 mm
- Printing time: 1 hour 19 minutes
- Material use: 17 grams (according to Makerbot 5th Generation)

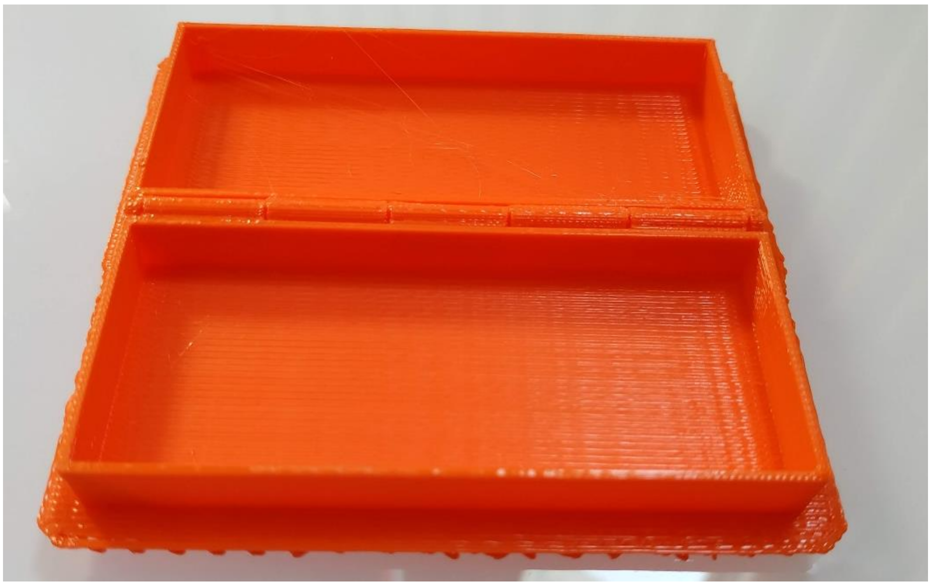


Figure 33. Hinge box modelled in SolidWorks (with raft)

4.2.2 Onshape

Production information

- Object dimension (height x length x width): (± 0.2) 16.9 x 70.1 x 29.7 mm
- Printing time: 1 hour 19 minutes
- Material use: 18 grams (according to Makerbot 5th Generation)

Figure 34. Hinge box modelled in Onshape (raft removed)

5 DISCUSSION

In mechanics, a hinge is an item that includes two objects fastened together by means of a pin or knuckles. Among daily life objects, more than 20 types of hinges are available. The idea of designing a hinge box came after the author watched the online training course on Lynda.com whose instructor is Kacie Hultgren. Meanwhile the online model was designed with Fusion 360, the author decided to design the hinge box with SolidWorks and Onshape. As the hinge box needs intermediate skill in design, this object is a suitable one to evaluate the modelling features and other functions within a MCAD software.

During the modelling process, the author created several models in different methods. This results an amount of versions of the box. Coincidentally, Onshape offers a flexible option that allows users to merge/branch main version to multiple versions. This helps users to adjust the design freely without affecting the original model. The accessibility of Onshape is one of the most prominent virtue that attracts users. However, Onshape focuses mainly on design and modelling, the software does not provide its own simulation package. Meanwhile, SolidWorks is able to offer simulation within its package. Moreover, SolidWorks overcomes Onshape not only in simulation but also in technical drawing. Technical drawing in SolidWorks follows a technical standard.

Nevertheless, one more aspect is worth to mention is the ability to export the model in STL file. As Makerbot Print requires printing file in STL or OBJ format, the author prefer STL to OBJ format because STL is more common and more suitable for FDM printer. Onshape is able to export directly STL file from an assembly (by holding right mouse button on the open tab and click on Export). However, to export STL file from an assembly in SolidWorks requires extra step. Users need to save the whole assembly as Part format (SLDPRT), and then save the Part format as STL format. This progress takes more time for users to prepare printing file.

As both designs were modelled in the same dimension, import to Makerbot Print, and have printed by Makerbot printer. The final products are more or less the same in printing time, and material use. Even though each object was modelled separately, Makerbot Print generates G-code and produces homogenous printing products.

6 CONCLUSION

As additive manufacturing starts picking up the interest from various industries, the need to approach 3D modelling software keeps growing. Despite the fact that plenty of modelling software are available, users need to consider various factors before making the decision of which software to use. As a result, this thesis offers readers a general understanding of 3D modelling software, as well as presents a selected few in numerous perspectives of additive manufacturing industry, such as the ability of mechanical CAD software, the growth of both desktop-based and cloud-based CAD software.

In additive manufacturing aspect, to design an object, from an idea to final products, users need to understand their own needs, to be proficient in using the software, to utilize the software for their own products. Therefore, users must consider many aspects to make the best out of the chosen software, such as features, accessibility, simulation package, or educational aspects. In other words, different modelling software serve different target users and deliver different products.

In this thesis, the author examined two prominent parametric modelling software: SolidWorks and Onshape. SolidWorks is a well-known desktop software; meanwhile Onshape is a new cloud-based software. Two software were employed to model an identical object, a hinge box includes two separated parts and a hinge, and then the author made a critical comparison based on the performance and the final product of each software. Moreover, in order to have a rational comparison, the author employed two methods, the SWOT analysis and AHP model. AHP model is renowned for its flexibility in conducting measurement within multi alternatives. These alternatives can be tangible or intangible object, in which AHP is able to evaluate each alternative without any compromising. According to AHP tool, the results presented that Onshape was most preferred with the final priority of 59%, and SolidWorks as a runner up with its priority of 41% approximately. This means the participant was preferred Onshape to SolidWorks in modelling an object.

Although SolidWorks is a prominent mechanical CAD software in engineer modelling industry, the availability of cloud-based software opens a new way of approaching modelling 3D object. Cloud-based software as Onshape requires no installation and no license; the software allow users to merge/branch different version when working on a design.

Even though cloud-based software is growing, it will need more time to catch up with desktop software. Desktop software still have an important role in engineering design as it provides professional environment to its users.

To make the most out of each software, users may need to utilize two or more software when working on a design. If users are technically inclined and have intermediate modelling skill, SolidWorks would be a suitable user interface. On the other hand, if users are keen hobbyists, cloud-based software as Onshape is an appropriate alternative. Since Onshape shares similar features to SolidWorks, users can design and model desired object. If Onshape brings 3D modelling software to users in a friendly approach, SolidWorks is a software that advances its users' design skill.

In classrooms, teachers can employ Onshape to follow up on student learning process or assign groups of students to work on a project simultaneously. Engineering students who are proficient in using SolidWorks will be able to make use of Onshape quickly. This will be a good practice for engineering students preparing for practical works in the future.

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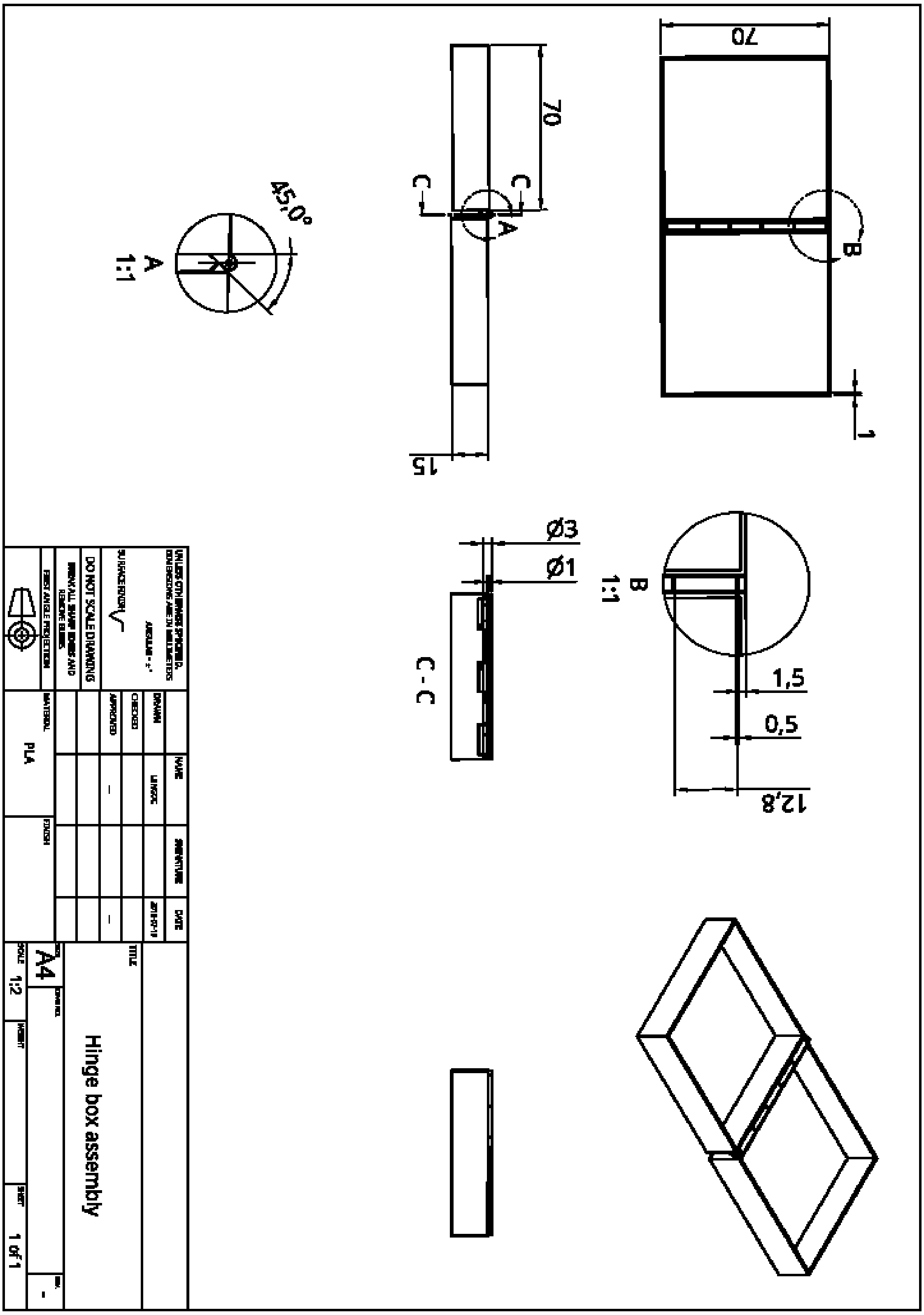
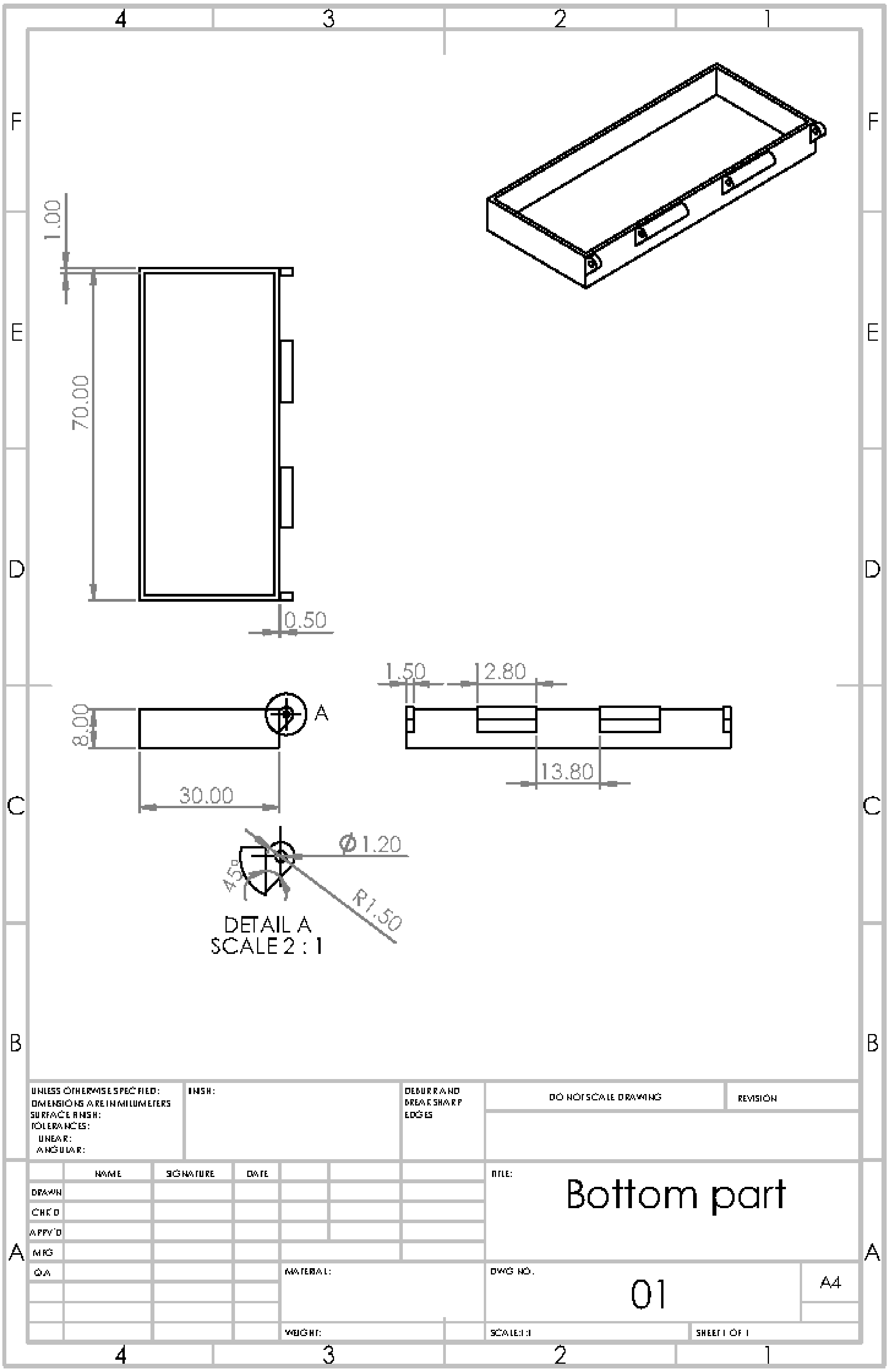
APPENDICES

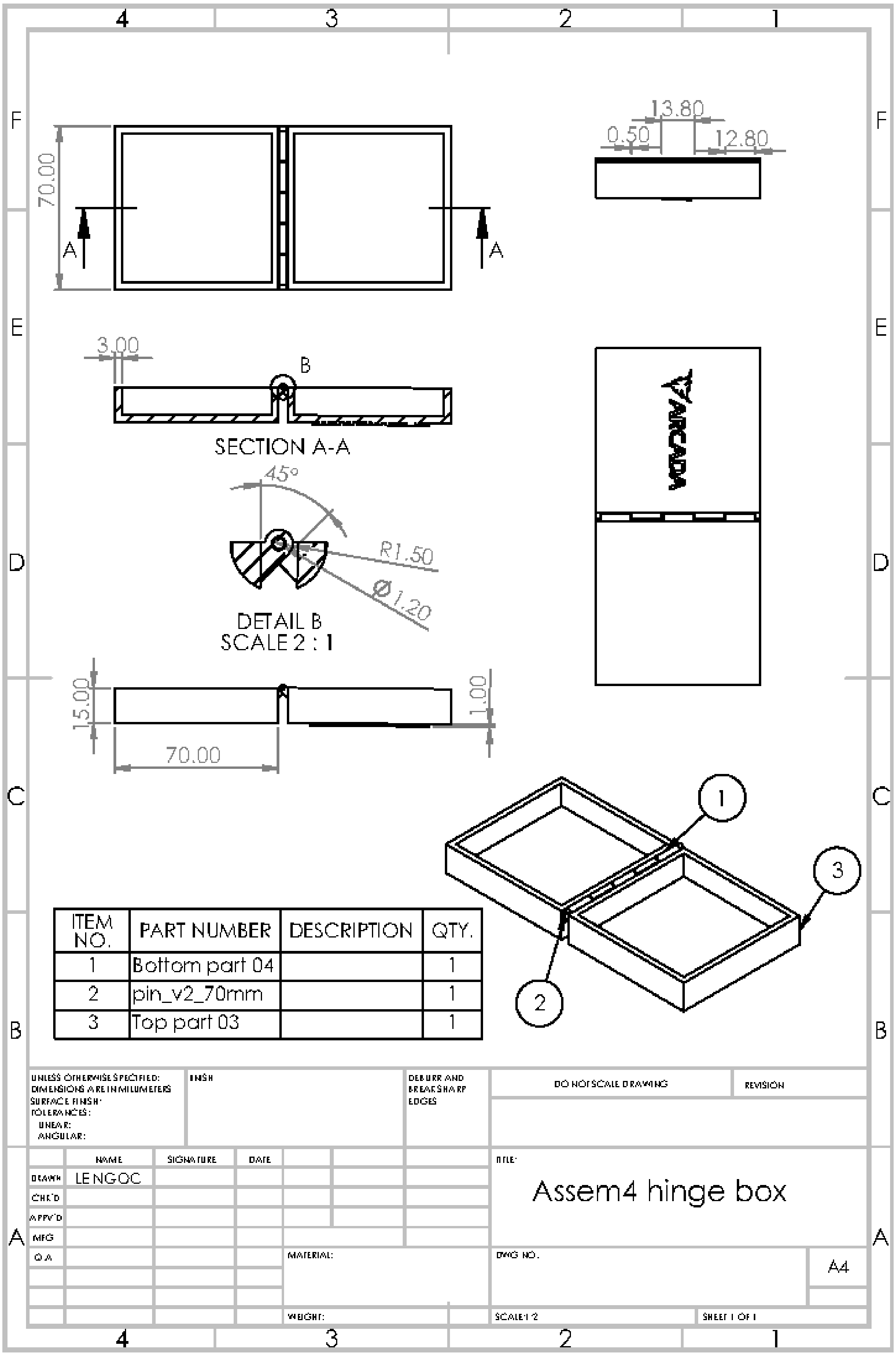
APPENDIX A Drawing Sheet in Onshape



APPENDIX B Drawing Sheet In SolidWorks



APPENDIX C BILL OF MATERIALS IN SOLIDWORKS



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Bottom part 04		1
2	pin_v2_70mm		1
3	Top part 03		1

APPENDIX D AHP CALCULATION IN MATRIX C

Location	SWARTH	NORTHW	U.MICH	VANDERB	CMU
SWARTH	1	1/4	1/3	1/3	7
NORTHW	4	1	2	3	7
U.MICH	3	1/2	1	3	6
VANDERB	3	1/3	1/3	1	4
CMU	1/7	1/7	1/6	1/4	1
Sum column	11.143	2.226	3.833	7.583	25.00

From the value in **Table 4**, we calculate the sum column and normalize the matrix by divide each element in a column to its sum. For example, in the first position (SWARTH, SWARTH), we obtain the normalized value as follows:

(SWARTH, SWARTH) = 1 ÷ 11.14286 = 0.0897

Similar to the calculation above, we obtain the normalize value in the position (NORTHW, SWARTH) = 4 ÷ 11.14286 = 0.3589

Thus, we have a matrix as below:

Location	SWARTH	NORTHW	U.MICH	VANDERB	CMU	Average row
SWARTH	0.0897	0.1123	0.0861	0.0439	0.2800	0.1225
NORTHW	0.3589	0.4492	0.5221	0.3956	0.2800	0.4011
U.MICH	0.2692	0.2246	0.2608	0.3956	0.2400	0.2780
VANDERB	0.2692	0.1497	0.0869	0.1318	0.1600	0.1595
CMU	0.0128	0.0641	0.0434	0.0329	0.0400	0.0386
Sum column	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

By calculating the average of each row, we obtain the criteria weight or the vector of relative weight $\boldsymbol{w}$ regards to criterion Location:

(SWARTH, NORTHW, U.MICH, VANDERB, CMU) = (0.1225, 0.4011, 0.2780, 0.1595, 0.0386)

To check the consistency ratio C.R, we need to determine the weight sum vector $\boldsymbol{w_s}$ by multiplying the A matrix with the vector of relative weight $\boldsymbol{w}$**.** Thus, we have the formula:

$$|\mathbf{A}| \,.\, \boldsymbol{w} = \boldsymbol{w_s}$$

| A | : pairwise comparison matrix C

w : vector of relative weight

$\boldsymbol{w_s}$: weight sum vector

The resulting number is the weight sum vector $\boldsymbol{w_s}$**:**

$$\begin{pmatrix} 1 & 1/4 & 1/3 & 1/3 & 7 \\ 4 & 1 & 2 & 3 & 7 \\ 3 & 1/2 & 1 & 3 & 6 \\ 3 & 1/3 & 1/3 & 1 & 4 \\ 1/7 & 1/7 & 1/6 & 1/4 & 1 \end{pmatrix} \begin{pmatrix} 0.1225 \\ 0.4011 \\ 0.2781 \\ 0.1595 \\ 0.0386 \end{pmatrix} = \begin{pmatrix} 0.6395 \\ 2.1970 \\ 1.5571 \\ 0.9084 \\ 0.1997 \end{pmatrix}$$

Now we want to know how good the principal eigenvector estimate $\boldsymbol{w}$ is. We find the consistency vector **λ** by multiplying the weight sum vector $\boldsymbol{w_s}$ with the inverse of the vector of relative weight $\boldsymbol{w}$. Hence, we have the formula:

$$\boldsymbol{\lambda} = \boldsymbol{w_s} \cdot \frac{\boldsymbol{1}}{\boldsymbol{w}}$$

Thus, we obtain the consistency vector **λ**

$$\begin{pmatrix} 0.6395 \\ 0.5169 \\ 0.4166 \\ 0.3240 \\ 0.2708 \end{pmatrix} \begin{pmatrix} 1/0.1225 \\ 1/0.4011 \\ 1/0.2780 \\ 1/0.1595 \\ 1/0.0386 \end{pmatrix} = \begin{pmatrix} 5.2169 \\ 5.4775 \\ 5.6001 \\ 5.6936 \\ 5.1627 \end{pmatrix}$$

We adopt the average number of **λ** = (5.2169 + 5.4775 + 5.6001 + 5.6936 + 5.1627) ÷ 5 = 5.43022

We notice that if the matrix C is consistent, $\lambda_{max} = n = 5$.

The C.I value can be calculated according to the equation, we obtained the value of the consistency index: C.I = $\frac{5.4302-4}{5-1} = 0.10756$

The value of R.I for a matrix 5 x 5 is 1.12

We have the consistency ratio as follow:

$$C.R = \frac{C.I}{R.I} = \frac{0.10756}{1.12} = 0.096$$

As the C.R value is in the range $0.01 < C.R = 0.096 < 0.10$, the pairwise comparison matrix C is consistent.