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Continuous improvement of a machining process by designing a new jig

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Sampath Kumar Senthil Kumar

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KEYWORDS

Jigs and fixtures, Six Sigma for design, SOLIDWORKS, Continuous improvement.

ABSTRACT

This thesis report gives an insight on how an often overlooked, jig and fixture used as a manufacturing aid to produce a product and essential for delivering products reliably and repeatedly with high quality. This continuous improvement project of an exciting machining process of winding cones used overhead garage doors. The improvement was a necessity with a forecast for 2019 estimating the need for 43% faster production cycle (takt time) compared to the previous year. Hence, the main objective was to reduce the machining time required per part by designing a modular jig system, ideally with 12 parts per cycle.

To make the work in an organized structure the project was dived into four phases namely: research, design, machining and implementation. The research phase included in the study of the old jig in use, analysing the process and sketching the basic requirements. The design phase was based on the methodology of Design for Six Sigma methodology for the fixture. Different kind of jig components was designed and assembled using SOLIDWORKS CAD model. The critical review of design iteration was analysed using SWO analysis (short version of the standard SWOT analysis) for design.

The machining of most components of the jig was done in-house with tacit knowledge of the machinist instead of using CAM software's making it first of its kind project in developing knowledge management in the company for future jig requirements.

The critical outcomes of the project were harvested from the implementation phase. The newly machined modular jig system proved to have increased the number of parts machined per day by 32% with expected savings of more than €6000 per annum. The added benefit of a modular jig system was that one base (skeleton of the jig) could be used in machining different products. Also, future projects now have the intellectual and physical resources of making jigs and fixtures in-house. This drastically reduces the lead times for new parts, which is crucial for a small-medium enterprise stay competitive.

PALAVRAS CHAVE

Gabaritos e acessórios, Six Sigma para design, SOLIDWORKS, Melhoria contínua.

RESUMO

Este relatório dá uma visão sobre como um acessório usado pode auxiliar na produção de forma a produzir um produto e os elementos essenciais para a sua entrega de forma confiável e repetida com alta qualidade. Este é um projeto de melhoria contínua de um processo de maquinagem de cones de enrolamento, usados em portas de garagem suspensas. A melhoria surjiu de uma necessidade com a previsão para 2019, estimando a necessidade de um ciclo de produção 43% mais rápido (*takt time*) em comparação com o ano anterior. Assim, o objetivo principal passava por reduzir o tempo de maquinagem necessário por peça, projetando um sistema de gabarit modular, idealmente com 12 partes por ciclo.

Para realizar o trabalho numa estrutura organizada, o projeto foi dividido em quatro fases: pesquisa, projeto, maquinagem e implementação. As fases de pesquisa foram incluídas no estudo do antigo gabarit em uso, analisando o processo e esboçando os requisitos básicos. A fase de projeto foi baseada na metodologia de Design for Six Sigma para um dispositivo. Foram projetados e montados diferentes tipos de componentes de gabarit usando o modelo SOLIDWORKS CAD. A revisão crítica da iteração do projeto foi analisada usando a análise SWO (versão reduzida da análise SWOT convencional) para projeto.

A maquinagem da maioria dos componentes do gabarit foi feita internamente com conhecimento tácito do responsável técnico, recorrendo ao software CAM, tornando-o o primeiro de seu tipo no desenvolvimento da gestão do conhecimento na empresa para futuros requisitos de gabarit.

Os principais resultados e conclusões dos projetos foram descritos na fase de implementação. O sistema de gabarit modular recém-maquinado provou ter aumentado o número de peças maquinadas por hora em 32%, com economias comprovadas de mais de € 6.000 por ano. O benefício adicional de um sistema de gabarit modular consiste de criar uma base (esqueleto do gabarit) usada na maquinagem de diferentes produtos, e projetos futuros, permitindo à empresa deter os recursos intelectuais e físicos de criar gabarits e acessórios internos. Assim, foi reduzido drasticamente o tempo de espera para novas peças, o que é crucial para uma pequena-média empresa permanecer competitiva.

LIST OF SYMBOLS AND ABBREVIATIONS

LIST OF ABBREVIATIONS

TERM	DESIGNATION
2D	Two Dimensional
3D	Three Dimensional
AISI	American Iron and Steel Institute
AMS	Agile Manufacturing System
BOM	Bill Of Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
DFMA	Design For Manufacturing and Assembly
DFSS	Design For Six Sigma
DIN	Deutsche Institute
DMADV	Define Measure Analyse Design Verify
DNC	Direct Numerical Control
EDI	Electronic Data Exchange
EFS	Economic Feasibility Study
EUR	Euro currency
FEA	Finite Element Analysis
FEM	Finite Element Method
FMC	Flexible Manufacturing Cell
FMS	Flexible Manufacturing System
FOS	Factor of Safety
HSS	High Speed Steel
ISO	International Organization For Standardization

KPI	Key Performance Indicator
NC	Numerical Control
PCE	Process Efficiency Cycle
PO	Purchase Order
P/OM	Production and Operation Management
QMS	Quality Management System
SME	Small and Medium sized Enterprise
SMED	Single Minute Exchange of Die
SWO	Strength, Weakness and Opportunity
SWOT	Strength, Weakness, Opportunity and Threat
TFS	Technical Feasibility Analysis
UNC	Universal Naming Convention
UNS	Unified Numbering System
USD	United States dollar
VE	Virtual Enterprise
VSM	Visual Stream Mapping
WIP	Work In Progress

LIST OF UNITS

TERM	DESIGNATION
N	Newton
kN	kilo Newton
Pa	Pascal
GPa	Giga Pascal
MPa	Mega Pascal
kPa	kilo Pascal

kg	kilogram
s	seconds
mm	milli metre
K	kelvin

LIST OF SYMBOLS

TERM	DESIGNATION
€	euro
Ø	Diameter of a circle
µ	micro
min	minute (time)
%	Percent sign
ℝ	Set of real number
$	United States dollar
C	Cost of operation per hour (labour cost, energy, etc)
D	Expected demand
B	Breadth
H	Height
L	Length
t	Total time required for an order to produced
Tc	Total cost incurred for an order
X	Number of units produced per hour

GLOSSARY OF TERMS

TERM	DEFINITION
Chip to chip time	The time from when the cutter starts one cut to when it starts the second cut
Production cycle	The time period of the production process from raw materials to finished product.

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INTRODUCTION

1.1 Contextualization

1.2 Main goals

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1.5 Welcoming company

1.6 Project Timeline

1 INTRODUCTION

1.1 Contextualization

The development of machines and tools were accompanied by development in auxiliary equipment's, which help in increasing capacity and quality of products. Whenever `N-number´ of similar parts require additional operations such a drilling, milling and tapping etc, a tool-guiding and work-holding jig or fixture is introduced as a special equipment into these processes.

Designing these kinds of special equipments are one of the most important and time-consuming phases in the manufacturing process. Planning and making these setup could take up to 85-90% of the overall time required to produce a part [1]. The recent scarcity of highly skilled machinist has paved the way to automated fixture design via CAD techniques. And this trend is likely to continue in the future.

A jig is a special tool in which its primary objective is to locate a complete holding of the workpiece in an optimal position during any of the manufacturing or assembly processes. It helps a worker get the required work done faster, accurately and without fatigue. The one area designers or machinist have started to concentrate are on the ergonomics for the machine operators. How maximum productivity can be reaped using safe and comfortable work environment for the workers.

In this project, the concentration will be on the design language used in making a modular jig with higher capacity per cycle. And how it helps in reducing the machining time per part and the overall benefits of a modular jig system.

1.2 Main goals

The goals of the project are as follows: -

I. Analyse and identify areas of improvement from the old jig in use.
II. To identify the location, supporting and clamping methods for the part and design a jig to machine repetitive parts at a lower time per part as possible.
III. Design a new modular jig that has better ergonomics and capacity than the old jig in use.
IV. Try and machine and assemble the new modular jig in-house and reducing the making cost of the jig as much as possible.
V. CNC code optimization that helps in reducing the machining time per part.

1.3 Methodology

The project was divided into three phases namely: Research, design and machining. Before starting the research phase, a few days were spent analysing the old jig in use by machining parts in it. And this where the timing of the machining cycles was also recorded. Then research papers and books were referred to in the area of jig design, machining principles, advancement in jigs and fixtures, CNC coding optimization and clamping designs.

The design phase of the jig was inspired by the use of lean six sigma in the design process, addressed in the paper by Charles G. Kibble et al [2]. With the help of different tools mentioned in the paper, KPI´s and a structure was created. Based on that various iteration of the designs were also developed and the final one was selected based on the requirements set by the customer and company.

Machining phase was the longest phase. With the help of 3D CAD diagrams, CNC programming and expertise of the machinist on the floor individual component of the modular jig system was made in-house. Once the machining of the jig is finished, the new cycle time and old cycle time was compared to understand the improvement and the critical outcomes were presented in a report.

1.4 Thesis's structure

For this final year project, all the works have been divided into 4 chapters namely: introduction, literature review, development and conclusion.

Chapter-1, the introduction describes the research methodology and the goal of the project on making a new jig as a part continuous improvement. The overall scope of the project is explained well in this section with an introduction to the company the project was carried on.

Chapter-2, the literature review starts with the history of manufacturing and the type of machining in detail. Then one gets to know in depth about the milling process, its limits and tolerance, essential features of a jig, clamping and its types, materials used and types of production management. Also, detailed are the theories about SMED, DFSS and CNC programming.

Chapter-3 is about the development of the whole project. It starts with understanding and analysing the problem. Then extracting the general requirements of the project. It also details the company´s organizational structure. The core of the development is about the brainstorming session. Which are detailed by use of SWO analysis (Strength, Weakness and Opportunity). Then the report talks about the feasibility analysis, new jigs design in detail, FEM analysis and the new jig implementations and improvements. This section concludes by pointing out the outcome of the implementation.

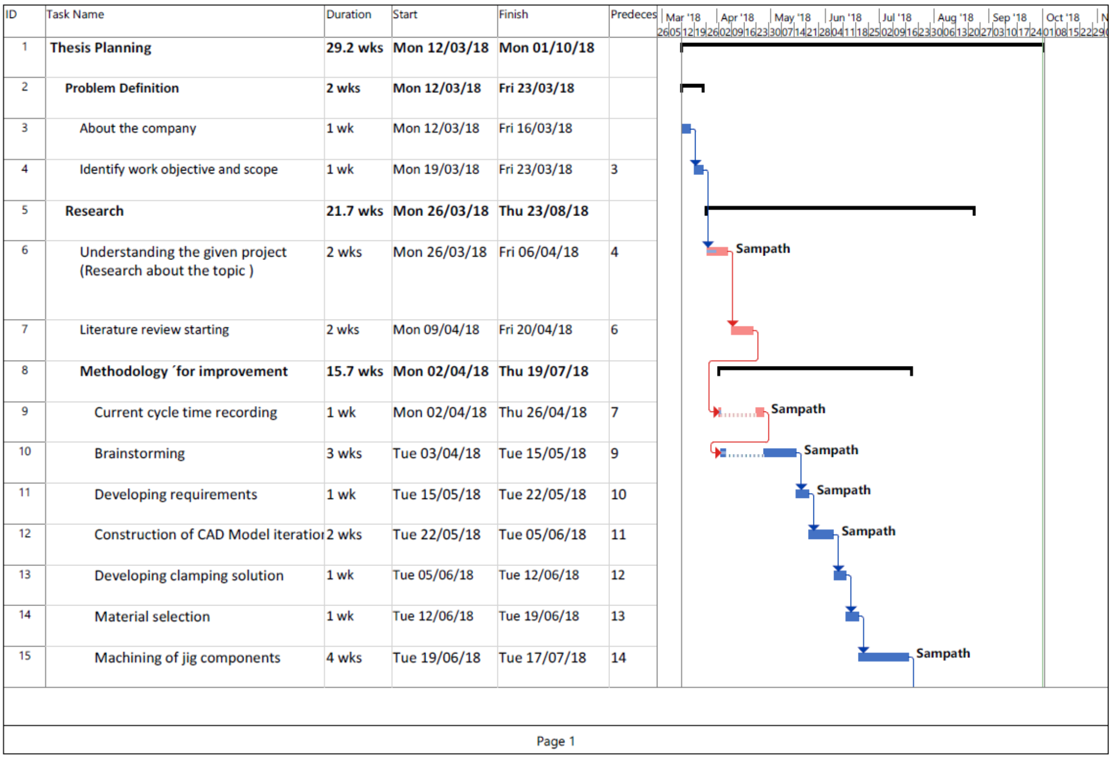
Finally, the project concludes with a brief summary of the entire project from start till the end in chapter-4 by highlighting the critical outcomes of the project.

1.5 Welcoming company

This project was developed in Fundwell Lda, a small-scale Aluminium and Zinc alloy die casting company located in Maia, Porto of Portugal. As part of their continuous improvement process.

1.6 Project timeline

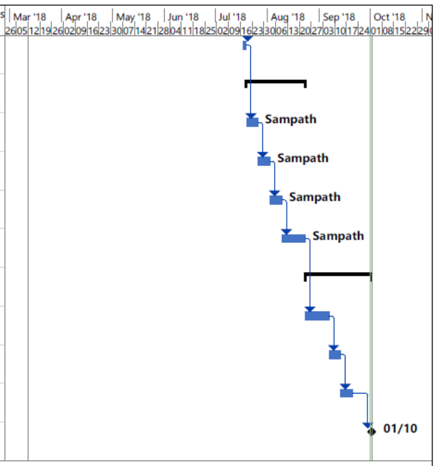
The project timeline is shown in Figure 1 and Figure 2.



ID	Task Name	Duration	Start	Finish	Predeces
1	**Thesis Planning**	**29.2 wks**	**Mon 12/03/18**	**Mon 01/10/18**	
2	**Problem Definition**	**2 wks**	**Mon 12/03/18**	**Fri 23/03/18**	
3	About the company	1 wk	Mon 12/03/18	Fri 16/03/18	
4	Identify work objective and scope	1 wk	Mon 19/03/18	Fri 23/03/18	3
5	**Research**	**21.7 wks**	**Mon 26/03/18**	**Thu 23/08/18**	
6	Understanding the given project (Research about the topic)	2 wks	Mon 26/03/18	Fri 06/04/18	4
7	Literature review starting	2 wks	Mon 09/04/18	Fri 20/04/18	6
8	**Methodology ´for improvement**	**15.7 wks**	**Mon 02/04/18**	**Thu 19/07/18**	
9	Current cycle time recording	1 wk	Mon 02/04/18	Thu 26/04/18	7
10	Brainstorming	3 wks	Tue 03/04/18	Tue 15/05/18	9
11	Developing requirements	1 wk	Tue 15/05/18	Tue 22/05/18	10
12	Construction of CAD Model iteratio	2 wks	Tue 22/05/18	Tue 05/06/18	11
13	Developing clamping solution	1 wk	Tue 05/06/18	Tue 12/06/18	12
14	Material selection	1 wk	Tue 12/06/18	Tue 19/06/18	13
15	Machining of jig components	4 wks	Tue 19/06/18	Tue 17/07/18	14

Figure 1 - Project timeline page 1 of 2

ID	Task Name	Duration	Start	Finish	Predeces
16	Test Assembly of jig	2 days	Tue 17/07/18	Thu 19/07/18	15
17	**Testing**	**5 wks**	**Thu 19/07/18**	**Thu 23/08/18**	
18	CNC coding for the new jig	1 wk	Thu 19/07/18	Thu 26/07/18	16
19	Collecting improvement data	1 wk	Thu 26/07/18	Thu 02/08/18	18
20	Analysis of critical outcome	1 wk	Thu 02/08/18	Thu 09/08/18	19
21	Drawing conclusion	2 wks	Thu 09/08/18	Thu 23/08/18	20
22	**Report writing**	**5.5 wks**	**Thu 23/08/18**	**Mon 01/10/18**	
23	Rough draft	2 wks	Thu 23/08/18	Thu 06/09/18	21
24	Final draft	1 wk	Thu 06/09/18	Thu 13/09/18	23
25	Professor verifciation and proof reading	1 wk	Thu 13/09/18	Thu 20/09/18	24
26	submisiion	0 wks	Mon 01/10/18	Mon 01/10/18	25



Page 2

Figure 2 - Project timeline page 2 of 2

BACKGROUND

2.1 Machining processes: Brief overview

2.2 Jigs for machining processes

2.3 Clamping system

2.4 Production management

2.5 Design for Six Sigma (DFSS)

2.6 CNC Programming

2 BACKGROUND

Often casting, forming or any kind of shaping process requires various methods of post-processing to derive the required dimension accuracy or surface quality. One of the most widely used processes is the machining process. In the sections to follow, one can get some basic understanding of the machining process and milling in detail.

2.1 Machining processes: Brief overview

Definition: -

The process of removal of material from the workpiece in order to produce specific geometry at the definite degree of accuracy and quality [3].

Evolution of machining : -

- **Stone age** – Used bone, stick and stone to cut material.
- **Metal age** – Made out of bronze and iron were used to shape material until the 17th century.
- **In 1774** – John Wilkinson built a precision machine for boring engine cylinder without the help of steam.
- **In 1818** – the first milling machine was invented by Whitney.
- **In Late 19th** century the Grinding machine was introduced.
- **In 1953-** the Numerical control technology (NC) paved way for computer numerical control (CNC) and direct numerical control (DNC).
- **Today** - Advancement in electronics and computer technologies, enable to post-process products at great speeds with an accuracy of ± 1 micrometre (µm) and non-stop.

2.1.1 Conventional machining processes

Conventional or traditional process in general, the cutting tools harder than workpiece and it requires physical contact between the two. Other newer types of technology called non-conventional machining process [4]. The 3 classic types of machining process are listed next.

Turning

It's a machining process that is used to reduce the outer diameter of rotational parts (Axially symmetric). Conventionally it's done in a lathe, where a cylindrical workpiece rotating about its axis is cut through by feeding a single-point cutting tool along the axis of the workpiece as shown in Figure 3. This process used to produce features like holes, grooves, threads, taper and various diameter steps and contours. It produces excellent finishes and high tolerances, it's used in high precision parts like fasteners and shafts [5].

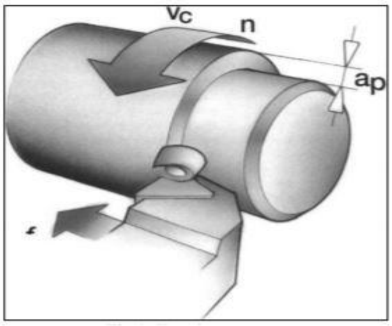


Figure 3 - Turning process, were n - spindle speed (RPM) and Vc - cutting speed (m/min) [5].

Drilling

The word drilling comes from a special tool that used to perform this operation called drill bits. The tool with more than one cutting edge is used to make holes or enlarge existing holes. There are several types of drilling machine, the most common being `hand-feed drilling machine´. The principle behind the operation is that feed motion is translated to the drill (Mostly vertically mounted to the spindle) with a primary cutting motion in rotatory motion along the spindle axis as shown in Figure 4 [6].

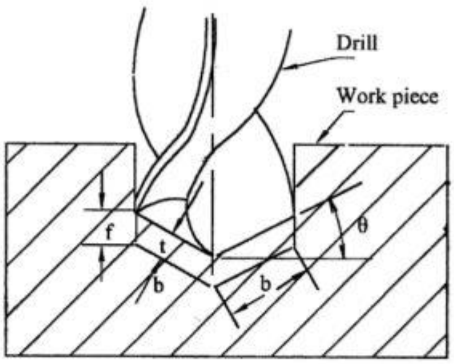


Figure 4 - Drilling process with f - feed per revolution of the drill, t - uncut chip thickness, b - drill radius and θ - point angle of the drill [6].

Milling

It's a process of generating machined surface by constant removal of material from the workpieces which is usually done at a low rate of feed and high spindle speed. It is done grouping number single point tools in a circular holder. The feature milling tool is that each cutting removes its share of material (even amount) in the form chips (as shown in Figure 5) than the continuous spiral chip in a turning process [7].

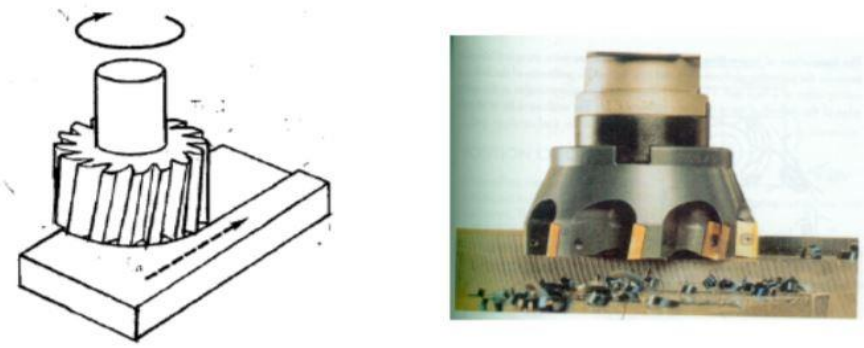


Figure 5 - Face milling cutter and its chip formation [7].

Boring

It's a process of making holes or circular profiles in an already carved contour. It's a little hard to understand at first the difference between boring, drilling and reaming. The one key difference is that boring is used to enlarge the drilled surfaces. It gives excellent finish on a drilled surface [8].

Grinding

It´s used as a finishing process mostly by employing an abrasive product, harder than the workpiece. The precision and surface finish obtained could be 10 times better than turning or milling. The abrasive grains in the tool remove a very little amount of material. There is controlled fracture happening on the abrasive tool once the grains wear [9].

2.1.2 Milling characteristics and applications

In this project, milling will be the primary activity in machining the jig. Hence, one will see various techniques and its application in this section.

Milling can be termed as interrupted cutting operation as the milling cutter enters and exit the work workpiece during each revolution creating an impact force and shock on every rotation. So, the tool and the cutter must be designed keeping these factors in mind.

The basic function is to produce a planar surface finish. But other contours and geometries can also be produced by using appropriate cutter tools, paths and shapers. There are 2 basic methods of milling as shown in Figure 6 [10].

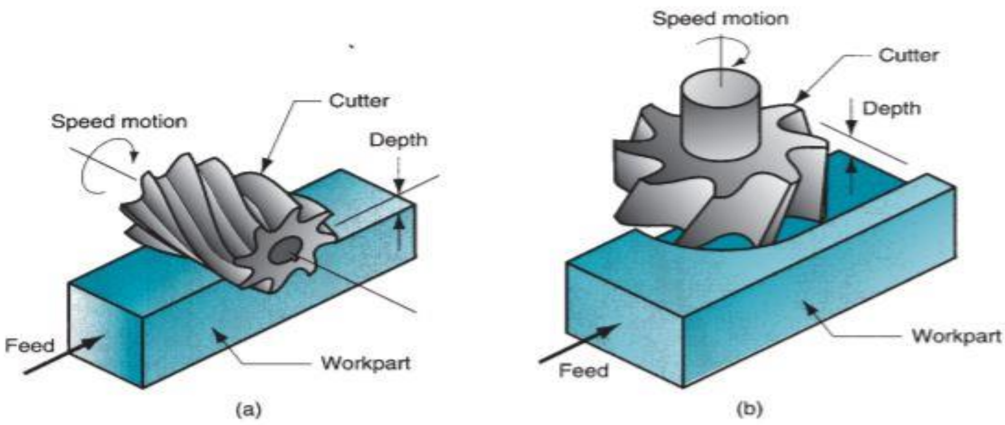


Figure 6 - (a) peripheral milling and (b) face milling [10].

1. **Peripheral or plain milling:** Axis of the tool is parallel to surface being machined.

- Slab milling – cutter width extends beyond the workpiece on both sides.
- Slot milling – cutter width lesser than workpiece width, thus creating slots.
- Side milling – cutter machines the side of the workpiece
- Straddle milling – cutting takes place on both sides of the work.
- Form milling – special profile teeth's that determines the shape of the slot.

2. **Face milling:** Axis of the tool is perpendicular to the surface being machined.

- Conventional face milling – diameter of the cutter greater than the workpiece width.
- Partial face milling – cutter overhangs to one side.
- End milling – cutter diameter is less than the width of the workpiece.
- Profile milling – outside of forming of a flat surface.
- Pocket milling – used to make a shallow pocket into flat parts.
- Surface contouring – ball nose cutter is used to cut curvilinear path close at the close interval as shown in Figure 7.

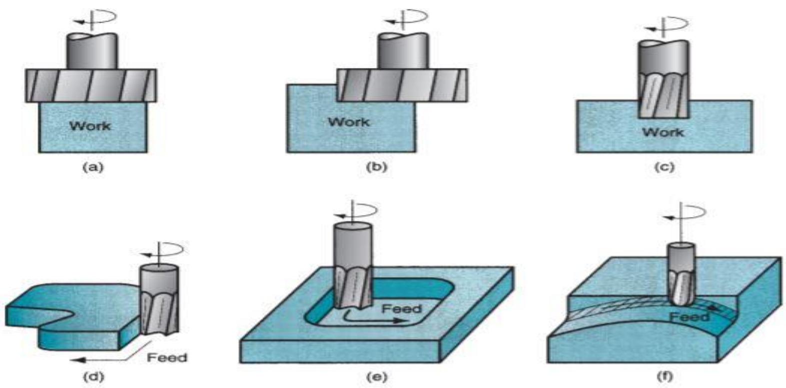


Figure 7 - (a) conventional face milling, (b)partial face milling, (c) end milling, (d) profile milling, (e) pocket milling, and (f) surface contouring [10].

Milling is used for a wide variety of purposes by using various cutting tools in different milling machines. Some of those are listed below [11]: -

- The flat surface in vertical, horizontal and inclined planes.
- For producing 3-D die or mould cavities and 2-D contouring cam profiles.
- For making slots, ribs, slitting flutes and various other salient features with different cutting tools.
- For making spur gears, straight-toothed bevels gears, worm wheels and sprockets.
- Long thread milling on large lead screws, power screws, worms etc and short thread milling for small size fastening screws and bolts.

2.1.3 Milling machines

Milling machines can be classified into two types: horizontal milling machine and vertical milling machine, based on the spindle rotation is relative to the workpiece axis as shown in Figure 8.

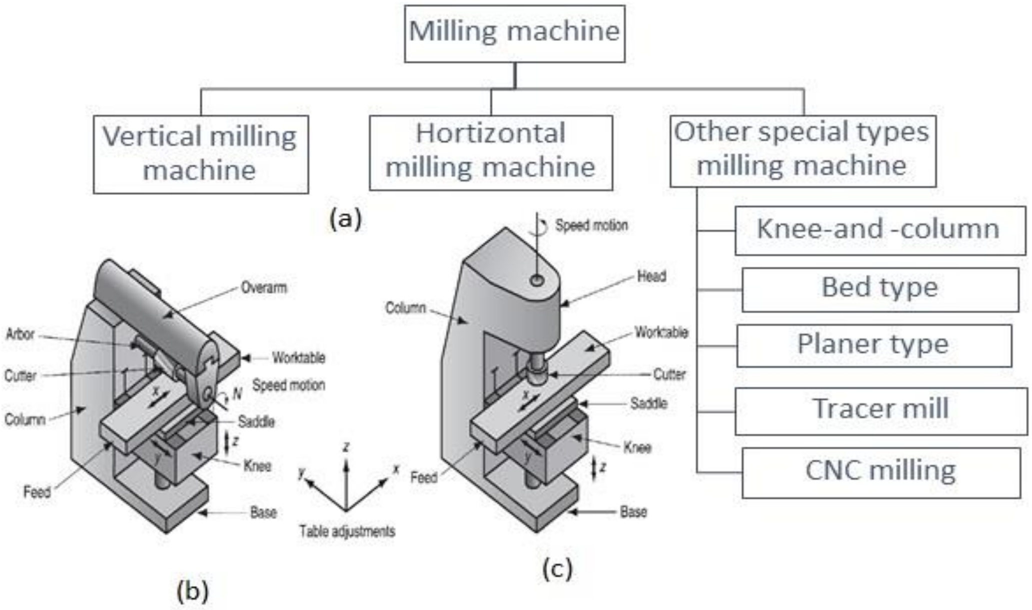


Figure 8 - (a) classification of milling machine based on spindle rotation (b) horizontal milling machine (c) vertical milling machine [10].

But there are also various types of milling machine depending upon their special needs like knee-and -column, bed type, planner type, tracer and CNC milling etc [12]. In this project, one will primarily use a CNC milling machine for machining the new jig.

CNC milling machine is in which most of the milling operation and table movement etc are controlled by a computer-controlled system. They have high productivity and can be used in complex tasks like profile milling, pocket milling, surface contouring and die sinking with require very tight tolerances.

2.1.4 Tools used in milling processes

Tools used in milling process are commonly called as cutters. They help in removing material by their movement and produce 3-dimensional shapes with multi-edge cutting surfaces [13].

FEATURE OF A CUTTERS

Cutters come in various variety depending upon specific kind of operations needed. But certain features are common in explaining the type cutter used. They are listed below [14]: -

- **Shape** – the overall shape of the tool.
- **Flutes / Teeth** – Helical grooves running up the cutter and along the edge is called teeth. The words flute and cutter are interchangeable words.
- **Helix** angle – It sets the gradual entry of the tool onto the material as shown in Figure 9 - Features of an endmill with 2 teeth´s [15].
- **Shank** – Cylindrical part of the cutting tool that is attached to the milling machine.
- **Centre cutting** - Orientation of the cutting tool.
- **Roughing** – It’s a configuration made using serrated teeth´s held in breaking material into smaller chips.
- **Coating** - For improving surface finish, cutting speed and increasing tool life.

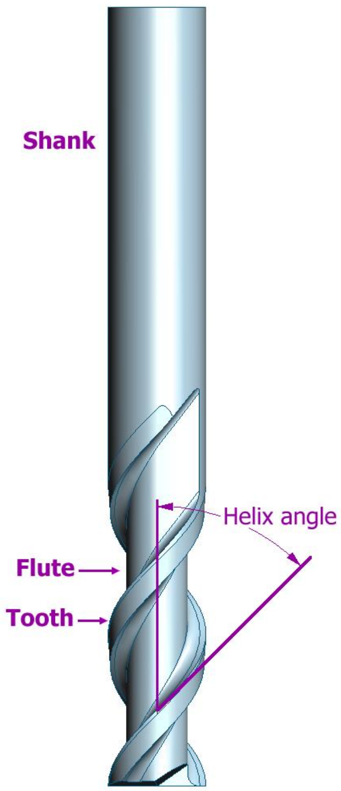


Figure 9 - Features of an endmill with 2 teeth´s [15].

TYPE OF MILL CUTTERS

Listed below are the most common types of cutters [13]: -

- **End mill** - Most common milling cutters, available in various lengths, diameters and types. End mills can be centre cutting (cutting edges on both ends face ad side) or non-centre cutting (cutting edges only on the side) as shown in Figure 10.

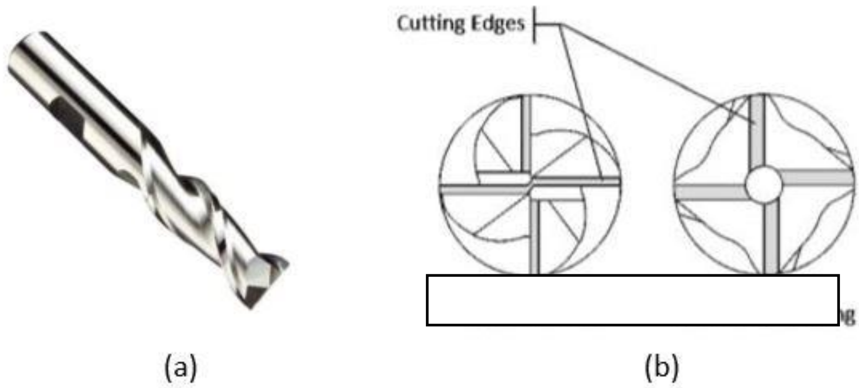


Figure 10 - (a) Endmill (b) centre (left) and non-centre cutting (right) [13].

- **Flutes** – Spiral shaped cutting edges help in chip escape when performing slot or pocket. An important parameter to consider while using flutes is “chip load”. It´s how thick the material is removed by each cutting edge. So, the number of flutes required depends on the material to be milled.
- **Drills** – Holes are the most common feature in CNC machining. There are several types of drilling tools used with the most common being twist drills. They have excellent removal rate better than equivalent endmills. A Sample twist drill is shown in Figure 11.

Figure 11 - Twist drill with conical cutting tip [13].

- **Taps** – Used to make an internal thread of specific size and pitch. They require perquisite hole generally little smaller in diameter than the actual size of the screw diameter. For example, M5 Tap will require a perquisite hole with 4.2 mm in diameter.

TOOL HOLDERS

Tool holders are used in adopting different shapes and sizes of tools accurately and securely to the spindle. The general anatomy of a tool holder is shown in Figure 12 and explained below: -

Figure 12 - Tool holder anatomy [13].

The solid conical shape at the top of the holder is called a shank. They come different shaped in according to the machine taper standards such as R8, NT 40, CAT 40, BT 40. In this project, a HAAS VF- 2 SS will be used for machining the jig and for machining the part. Figure 13 shows the most common CT and BT specification.

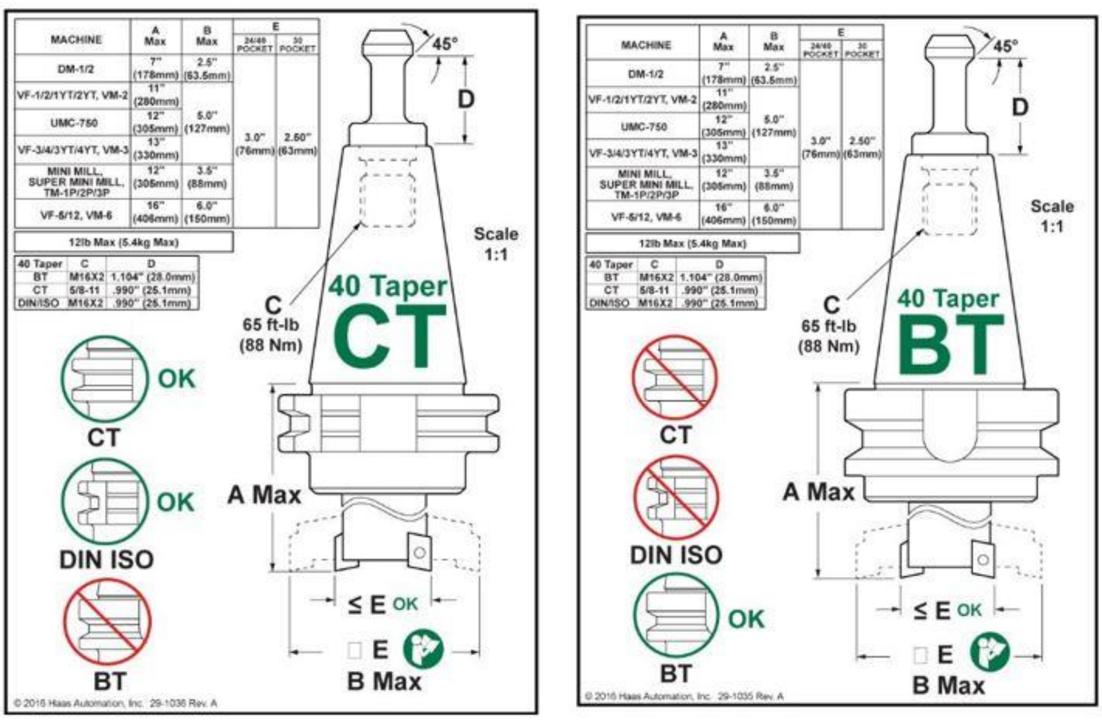


Figure 13 - CT and BT specification for HAAS VF-2 SS [16].

TOOL MATERIAL AND COATING

There are a variety of materials to choose for machining depending upon cost, type of part material and speed at which one needs to do. Listed below are the most used material in the industry [13]: -

- **High-Speed Steel (HSS)** – Most used material because of it good wear and heat resistance. It's relatively less expensive.
- **Cobalt** – Cobalt is a M42 tool steel with 8% cobalt content. It's expensive but provide better wear and heat resistance than HSS, hence faster material removal rates.
- **Solid carbide** – Carbide is harder but brittle. It possesses great heat and wears resistance but chips instead of wear, making the tool unusable in most circumstances. Hence, its mostly used in finishing application. They are also much expensive than the previous two.

Apart from the materials of the tool, coating the tool will help in added benefit to tools existing physical characteristics. Coatings include Titanium Nitride (TiN), Titanium Carbonitride (TiCN) and Aluminium Titanium Nitride (ALTiN). Titanium nitride, in general, is good against wear and hard material for machinings like stainless steel and cast iron. It can be unidentified by a gold coloured coating on top of the tools cutting surface.

2.1.5 Fit and Tolerance – DIN ISO 286

It is impossible to manufacture a part or component in an exact same size or geometry. Variations start from drawings and some degree of deviation should be accountable. Tolerance is the acceptable deviation from a standard or a requirement. The large variation could lead to non-functionality and small variation leads to economic issues of the part [19].

Fit may be defined as the degree of tightness and looseness between two moving parts. They can be classified into 3 types: Clearance, transition and interference fit. A detailed description of these classifications is given in Table 1.

Table 1 - Description of Preferred Fits [16].

	ISO SYMBOLS HOLE BASIS	ISO SYMBOLS SHAFT BASIS	DESCRIPTION	
CLEARANCE FIT	H11 / c11	C11 / h11	**Loose running fit** for wide commercial tolerances or allowances on external members	
	H9 / d9	D9 / h9	**Free running fit** not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures.	↑ MORE CLEARANCE
	H8 / f7	F8 / h6	**Close Running fit** for running on accurate machines and for accurate moderate speeds and journal pressures.	
	H7 /g6	G7 / h6	**The sliding fit** not intended to run freely, but to move and turn freely and locate accurately.	
	H7/ h6	H7 / h6	**Locational clearance fit** provides a snug fit for locating stationary parts but can be freely assembled and disassembled	
TRANSITION FIT	H7 / k6	K7 / h6	**Locational transition fit** for accurate location, a compromise between clearance and interference	
	H7 / n6	N7 / h6	**Locational transition fit** for the more accurate location where greater interference is permissible.	
INTERFERENCE FIT	H7 / p6[a]	P7 / h6	**The locational interference fit** for parts requiring rigidity and alignment with a prime accuracy of location but without special bore pressure requirements.	
	H7 / s6	S7 / h6	**Medium drive fit** for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron.	MORE INTERFERENCE ↓
	H7 / u6	U7 / h6	**Force fit** suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical.	

[a] Transition fit for basic sizes in the range from 0 through 3mm

2.1.6 Accuracy required in the milling process

According to HEIDENHAIN [17] accuracy of any machining process is influenced by various factors. It's easy when the customer gives the tolerance required in the specs sheet for the parts to be produced, but it's not the same in every case. For example, developing a prototype requires designers to keep in mind process and machining limitations in achieving the close to exact product one are trying to design. It´s a critical aspect of modern-day manufacturing to go from design-to-prototype-production as soon as possible. Organisations are trying to get it right in their first try with the help of design, simulation and analytic software's. listed below are some key factors that might influence inaccuracy in workpiece: -

- **CAD** (Computer Aided Design)– while designing in CAD one needs to keep in mind the contours that are applied. Sometimes it´s hard to transform these contours in the CAM (Computer Aided Manufacturing) phase. So, it's important to be as accurate as possible in this phase.
- **CAM –** Generally the CAM gets its input from a CAD model. The cam software calculates point by point the tool path for the milling strategy and tool compensation values for CAD geometry. So, it vital that CAD model should be spot on and should consider CAM Constraints.
- **CNC** (Computerised Numerical Control) – This control program converts the points in t axial movements and velocity profiles. To make sure high surface finish deviation between adjacent paths must remain smaller than defined.

For example, Datron M10-PRO with precision linear glass scale can perform HSM at 40000rpms with an accuracy of 5 microns. But can be only done in certain temperature conditions. Although an accuracy of ±0.02mm (20 microns) can be achieved in most of the operations [18].

2.2 Jigs for machining processes

K. Venkataraman [20] defines a jig as a device in which the components gets clamped on at a specific location to lock movements across the 12 degrees of freedom. So, that a cutting tool could be used to perform one or more operations. They are devices on their own that help in loading and unloading of components with ease. They are clamped in unique positions.

2.2.1 Why jigs are needed

There are a lot of reasons why one may need a jig. For some, they are necessary and others are for productivity and convenience. A few reasons are listed below from Spogel [21] and Okpala et al [22] in the context of this project: -

- Help to facilitate productivity by making interchangeability of workpieces possible saving a huge amount of cost in production.

- One doesn’t need highly skilled labours (although it might change in a few years’ time with higher axial operation machines are employed in production) as operators when you employ jig-based production (usually repetitive activities and setup) as it cuts down on labour cost.
- The key thing in terms of quality products produced by eliminating variation and maintain a high degree of accuracy helps in easy assembly of parts.
- The repeatability and exact reproduction of the part before is a primary reason one use jigs.
- Reduce the need for quality control measures.
- Increased safety and machining happen in a closed environment.
- It helps in high operating conditions like multiple tools application simultaneously on one single workpiece. Higher spindle speed and feed-rate due to the availability of clamping on jigs.

2.2.2 Elements of jig

Okpala et al [22] say that the body, clamping devices, locating devices and tool guide are major elements of jigs. Each of them is detailed in the section below and illustrated in Figure 14.

The Body: It’s made by either welding different part of metal usually mild steel or cast iron and then heats treated for stress reduction as it should accommodate and support the workpiece. Some common body types are channel body type, box body type, plane, leaf and built up body type.

Locating Devices: Its usually made of hardened steel of various design according to the workpiece. The pin is the most popular one applied. But there are classifications is pins as well, namely: -

- **Locating pins** - Used for the location of the workpiece when completed.
- **Jack pins** – They are used in workpieces where their dimension keeps changing. It’s a spring-loaded mechanism and rises as the weight of the part decreases. The workpiece is firmly fixed using the locking screws.
- **Support / Rest pins** – These are particularly useful for curved surface but can be used on flat surfaces too. Flathead often provides support to machine surface as more contact is accessible.

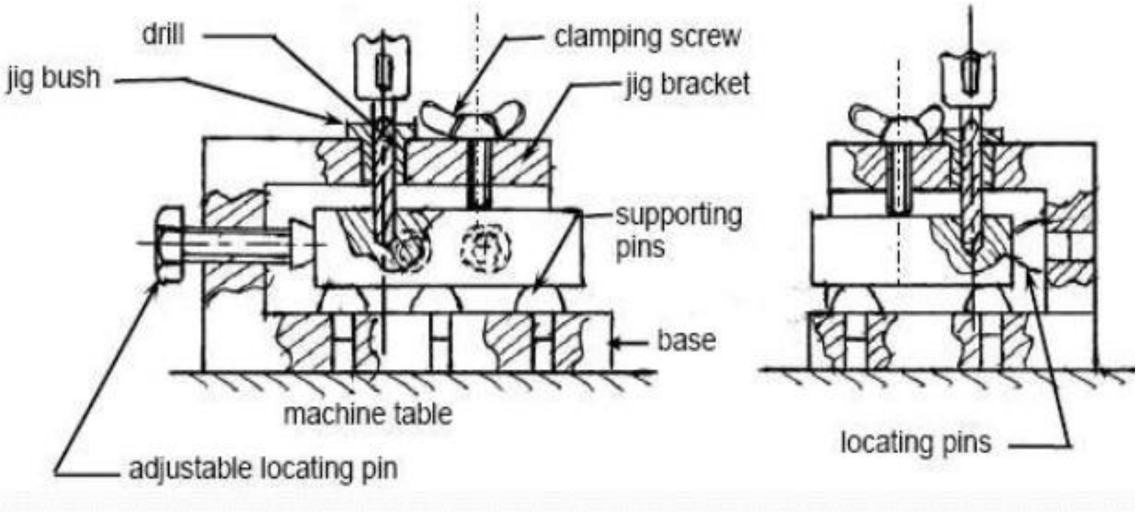


Figure 14 - Major elements of a Jig [21].

Tool guide/Jig Bushing: Jig bushes are used in drilling and boring. It helps the drill pass through the bush, into the hole of the jig. They are made of tool steel to avoid cracking but harden steel are preferred for reamers, drills and traps. The jig bushing can be categorized into three types, Linear, press-fit and renewable wearing bushes.

Clamping device: They help in adding strong holding points to the workpieces. They must be easy to operate to be effective in the manufacturing process. One will study clamping in detail in later sections.

2.2.3 Types of jigs

Edward G. Hoffman [23] has classified drill jigs as 2 types: -

- **Closed jigs** – simple one side operation.
- **Open Jigs** – more than one side operation.

Template jig: They are basic kind of jig that is not expensive. Generally used for accuracy than speed. They are used with bushing and when they don't have a bushing, the whole jig is hardened.

Plate jig: They are like template jig but have inbuilt clamps and raised jig through legs. Depending upon a number of parts, the addition of brushing is decided.

Sandwich jigs: Kind of plate jig with a back plate. It's ideal for the thin and soft part. An illustration is shown in Figure 15.

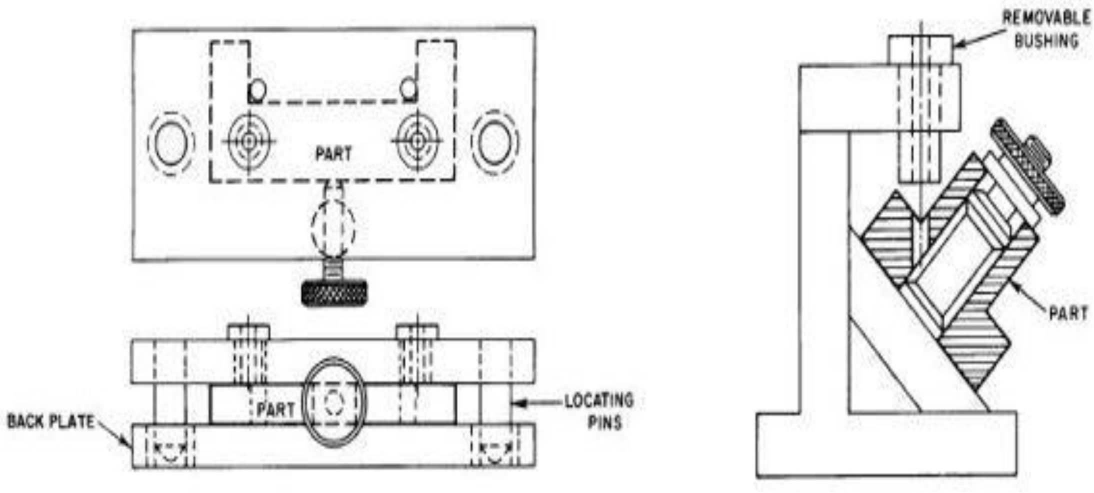


Figure 15 - Sandwich jig (left) and Angle jig (Right) [21].

Angle – Plate jig: Pulleys, collars and gears are some of the parts that use this type of jig. They are employed in parts where clearance is a problem. Another version of this is called the modified angle – plate which is used for machining angle more than 90 degrees.

Box jig: This type of jigs allows the workpiece to be machined in every side possible without repositioning of the workpiece.

Channel jig: They are the simplest form of box jig withheld by 2 sides and machined on the third side. They could also be raised if needed to operate on the third side.

Leaf jig: Box jig with leaf-like a hinge with a handle for easier unloading and loading. The size and workpiece location make´s leaf jig different from box jig.

Trunnion jig: This type of jigs are used for large odd shaped parts with several separate plate type jigs. The workpiece is kept in a box type jig and then loaded on the trunnion.

Pump jig: The lever activated jig makes this tool very fast to load and unload. A great deal time is saved using this jig.

Indexing jig: Used to accurately space holes. Large indexing jigs are called rotatory jigs. The jig itself uses the part itself or a reference plate and a plunger.

Multistation jig: The main feature of the jig is the way it locates the work. One could be for drill and other could be for reamed etc. Commonly used on multiple-spindle models. A collective image is shown in Figure 16.

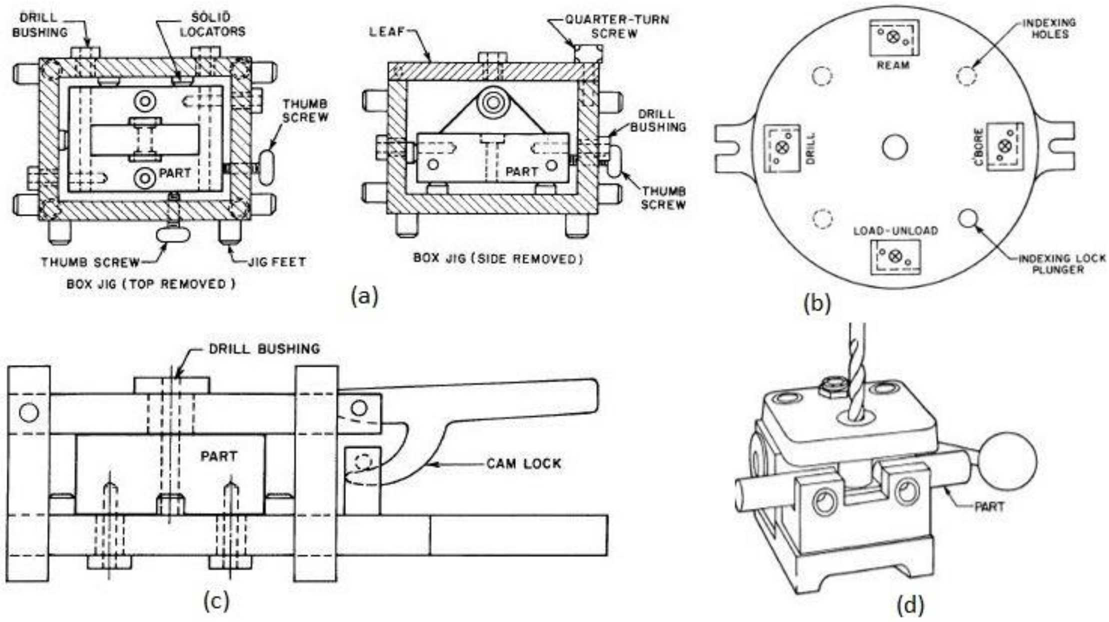


Figure 16 - (a) Box jig (b) Multistation jig (c) Leaf jig (d) Trunnion jig [22].

2.3 Clamping systems

Edward G. Hoffman [23] terms clamping systems as part of *workholder*. Generally identified as part of the jig or fixture. The purpose of a clamp is to securely hold the workpiece against the locators throughout the machining cycle. To do so, clamping must meet the following criteria that a tool designer should keep in mind: -

- Strong enough to hold the part and resist momentum.
- Should not deform the workpiece.
- Allow fast loading and unloading of the workpiece.

2.3.1 Principles of clamping position

The locator must ensure that the workpiece is properly held by the workholder relative the cutting tool, repeatedly for `n´ number of cycles.

“Referencing” is a dual process of positioning the workpiece with respect to workholder, and the workholder in relative to the cutting tool. Depending upon the type of operation the referencing differs. For example, drilling is done with the help of bushing and with the fixture, it’s done with fixture keys, probes etc.

“Repeatability” is the ability of the workholder to consistently produce parts within the allowed tolerance. This can only be achieved with proper referencing of the workpiece to the tool [24].

Mechanics of locating

Erik K. Henriksen [25] describes that the workpiece free in space can move in an infinite number of direction. But it can be broken down in 12 directions (as shown in Figure 17) or `Degree of freedom´. Movements must be restricted in these 12 directions to ensure accuracy.

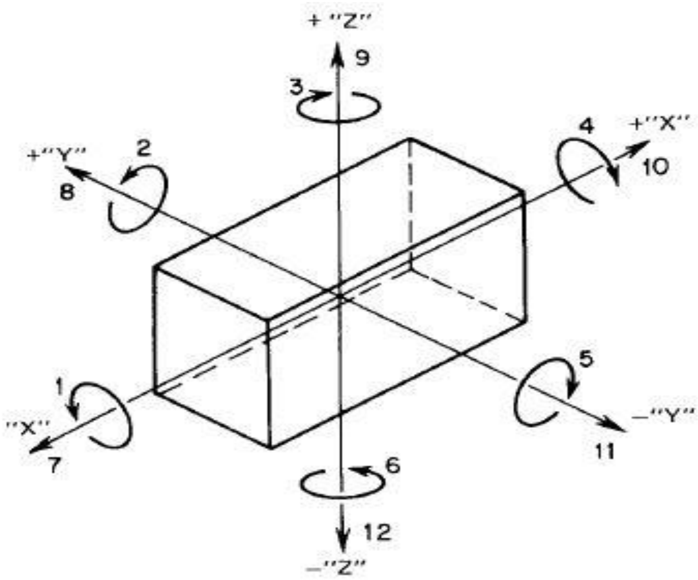


Figure 17 - The 12 - degrees of freedom [25].

There numerous ways to lock the movement of the part, but it differs according to the dimension, operation and level of accuracy one is trying to achieve in the finished part. Some classic examples are using pins as locators. If a 3-pin is used it can restrict movement in 5 directions or if a 5-pin is used it can restrict in 8 directions as shown in Figure 18.

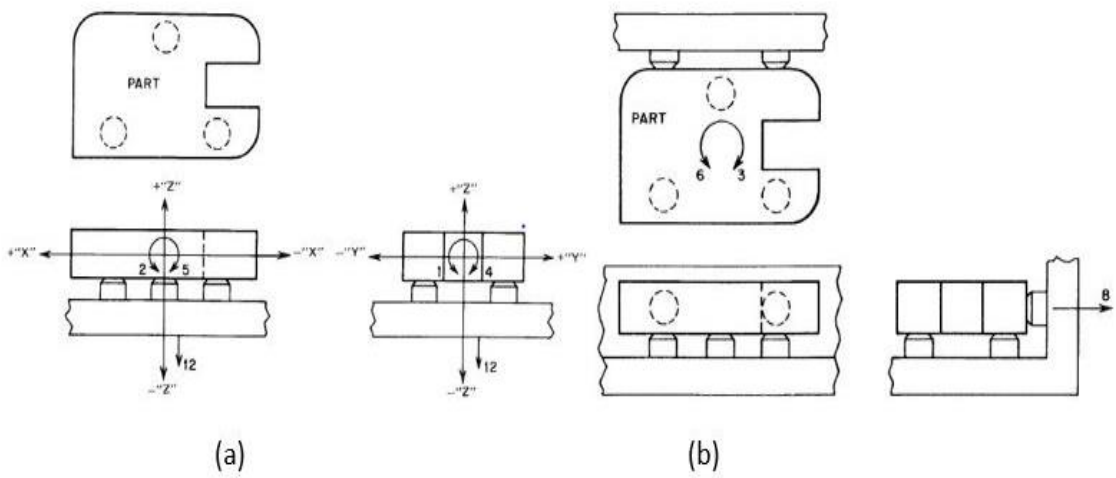


Figure 18 - (a) 3 - pin base (b) 5 - pin base [25].

2.3.2 Clamping force

The clamping force should counteract the reaction force from the tool. The direction of the tool forces depends upon the type of operation employed (as shown in Figure 19). It's important for the designer to understand these cutting forces and use it to their advantage of holding the part together. The type and amount of clamping force needed are usually predetermined from the tool force working on it [23].

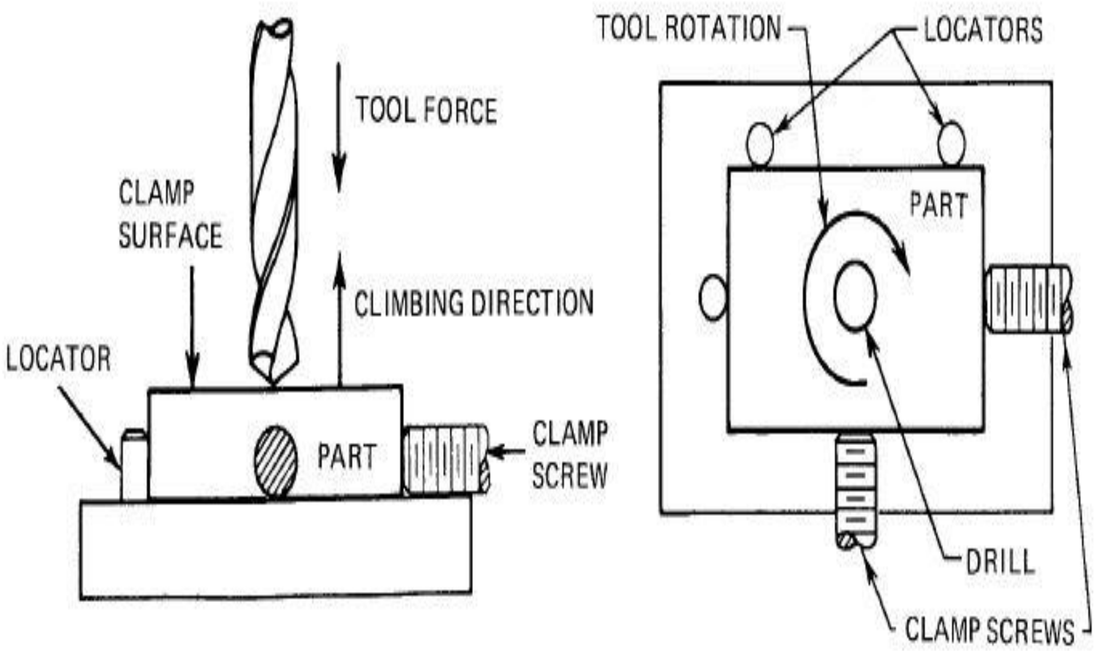


Figure 19 - Forces and clamping are involved in drilling operation [26].

2.3.3 Types of clamps

Various types of clamps are needed depending upon design and activities related to the process. But according to V. Jani [27], it can be categorised into the following types: -

1. Manual
2. Electrical
3. Hydraulic
4. Pneumatic

A brief comparison of the various characteristics of these clamps is discussed in Table 2.

Table 2 - Advantages and disadvantages of different types of clamps [27].

TYPES OF CLAMP	ADVANTAGES	DISADVANTAGES
MANUAL	• Simple and easy way to hold parts by directly applying force in the part. • For example, like toggle clamps allow for complete accessibility of parts allowing for faster part changes. • Very cheap and highly versatile in its uses and can be used in various part of the workshop.	• Cannot be used in strong vibrating parts. • Not ideal for machining high number of parts per cycle. • High enough clamping force but not as much as others.
ELECTRIC	• Best in precision control positioning. • Good repeatability and great adaptability. • No fluid leaks and can be reprogrammed for greater control of velocity, torque and force applied.	• More expensive than the others. • Can get overheated, limiting some circumstances of operation. • They could be bulky and heavy.
HYDRAULIC	• Produces greater clamping force than any other type of clamps. • Hydraulic motors can produce a best horsepower-to-weight ratio. • Can hold constant force due to the incompressibility of the fluids.	• Leakage of fluids could lead to problems. • Need auxiliary component setup like motor, pumps valves and heat exchanger etc. • Extremely large for installation.
PNEUMATIC	• Accurate linear motion and repeatability. • Simple and easy to install & use. • Generally lightweight and durable. • Can be used in a high-temperature environment. • No motors needed hence no magnetic interference.	• Pressure loss and air compressibility lead to low efficiency. • Special purpose (like high-efficiency air pneumatic) are pricier and bulky.

Listed are few of the common type of clamps: -

- **Strap clamp** – A. Rane [28] describes strap clamps as very simple and reliable clamping devices by applying clamping force using a spring-loaded nut. They are made of rectangular plate and act as levers. One end of the clamp presses against the workpiece and the other against the heel pin as shown in Figure 20.
- **Screw clamp** – They are used for light clamping used like a screw by rotating and tightening. The clamping area is increased by providing a pad. But its weakness is it takes a lot of time and effort to clamp and unclamp. The clamping pressure depends on the workpiece.

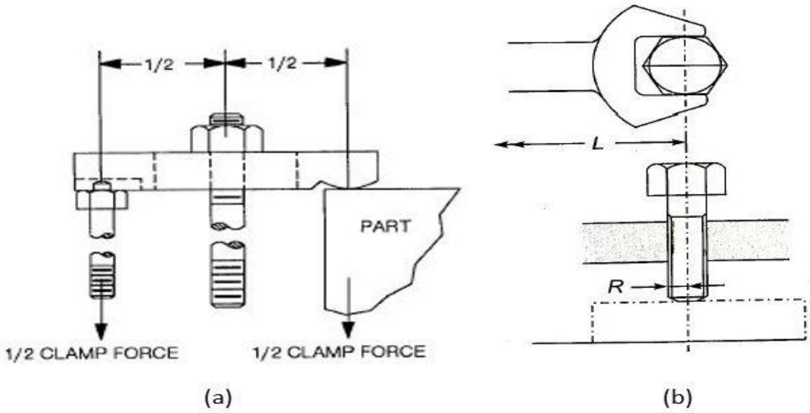


Figure 20 - (a) Strap clamp (b) Screw clamp [28].

- **Swing clamp** – It´s one of the most advanced clamping solution for good clamping force, great productivity and repeatability. They are available in a variety all types of clamps. They operate by a rotating handle that rotates either side by an angle. They have a clamping force for of between 700N to 9.5kN says fixture holding company `fixtureworks´[29]. A detailed illustration is shown in Figure 21.

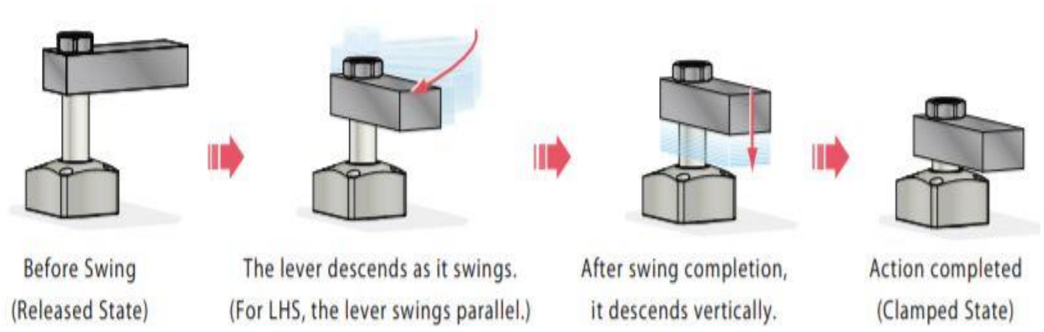


Figure 21 - Pneumatic swing clamp action explained [29].

- **Toggle action clamp** – Fast action clamps that have natural ability to move completely free of the work. The four main basic actions of toggle clamps are: hold down, squeeze, pull and straight -line. They come in a variety of handle position, mounts and spindles. The one key advantage of toggle clamp is that they offer an excellent ratio of holding force to application force as seen in Figure 22 [23].

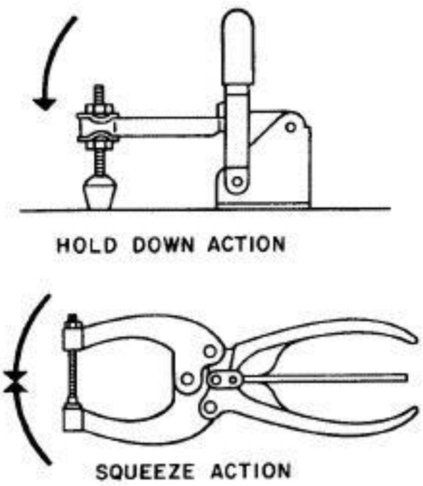


Figure 22 - Basic 4 types of action toggle clamp [23].

- **Vices and chuck** – A blank vice and chuck can be used for most of the jobs in hand by modifying the jaw. Due to tight budgets, one chuck is used for multiple jobs. Using a standard chuck and vice you can save in tool design time and cost, at the same time increase the efficiency.
- **Magnetic clamping system** – They are electromagnetic clamps that are known to provide excellent clamping, being it for a part or a plate. But have a few shortcomings due to the magnetic properties. Thanks to new advances in technology, it's now one of the most uniform clamping systems providing high surface quality, precision (20 microns) and increasing tool life. The major advantage is a massive reduction in setup times and can provide a clamping for of up to 384kN [30]. Shown in Figure 23 is the illustration of how the tool would work around a magnetic jig.

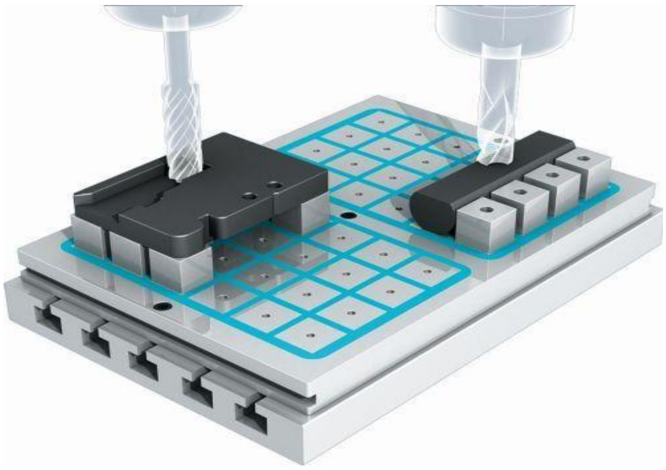


Figure 23 - Magnetic holding fixture for machining [30].

2.3.4 Pneumatic Cylinder Mechanism

Cylinders are the most important means of actuation in pneumatics. They function by transferring compressed air into motions.

Design of a cylinder

Most cylinders function by using piston rod as shown in Figure 24. A tube is closed on both ends of the cylinder. The direction of the piston rod is defined by the chamber in which the compressed air is allowed to flow. Then the force transferred to the piston rod.

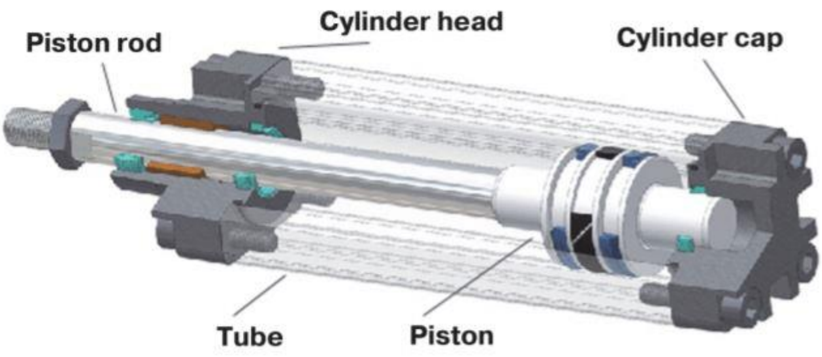


Figure 24 - Components of piston rod cylinder [31].

Diameter and Stroke

The *diameter* is the actual diameter of the piston rod. The force is dependent on the diameter of the cylinder. The *stroke* is the travel made by the piston rod in the influence of compressed air [31].

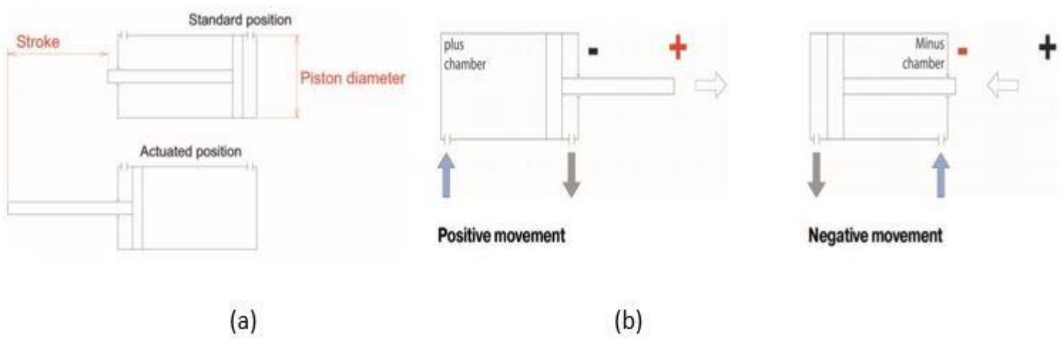


Figure 25 - (a) Diagrammatic representation of diameter and stroke (b) Movements of the cylinder [31].

There is two end position of a cylinder as shown in Figure 25 are listed [31]: -

- Positive / Plus – Furthest possible position of the piston rod or can be said as inflated.
- Negative / Minus - The opposite side of minus or deflated position.

Force calculation

Various formulas are required to find the force exerted by the cylinder.

The surface area of the piston:

$$A = \prod d^2/4 \text{ (Sq. units)} \qquad (1)$$

Force calculation:

$$F = P \cdot A \text{ (N)} \qquad (2)$$

Where `P´ is the operating pressure usually in bars or kilopascals.

2.3.5 Sophisticated jigs

Jigs and fixture are components that are often overlooked for improvements. But with markets becoming more and more competitive there is a need to get the product to market as soon as possible. However, custom jigs are produced for custom parts and machines.

One such technology is 3D printing also called additive manufacturing. `Stratasys Direct Manufacturing´ [32] provides some insight on how it not only reduces lead time but can also provide cost savings through reduced material consumption.

Figure 26 - On the left conventionally machined aluminium fixture for testing bumper support by BMW and on the right 3D printed with ABS thermoplastic fixture [33].

The fixture shown in left side of Figure 26 was inconvenient and heavy for workers to use, who manually held the fixture for each test. BMW saw an opportunity to increase the comfort and design employed 3D printed fixture (on right Figure 26). The result was a 72 % reduction in weight, 58% cost saving in cost per jig and 92% faster lead time.

Jon Cobb [33] cautions that it may not be ideal to use in processes that need chemical resistance (petroleum, solvents), thermal resistance (up to 473 K) and resilient mechanical properties. But at the same time, it's easy to replace the traditional fabrication process with 3D printing with huge savings in the manufacturing floor and in jig and fixture production.

2.3.6 Recent advances in jig design

M. Nategh et al [34] describes the zero clamping system as one that can hold standard baseplate with the part already fixed. They provide constant zero points without the need of realignment of the modular fixture, guaranteeing a fast and safe exchange of fixtures. The accuracy and repeatability are rated at 3 microns. An exploded view is shown in Figure 27.

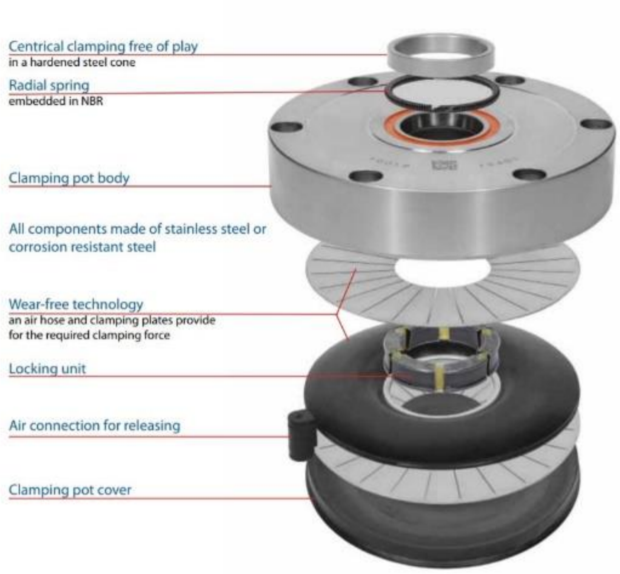


Figure 27 - Zero clamping system in exploded view and assembly view [34].

2.4 Production management

S. Gupta et al. [35] describes production and operation management (P/OM) as the study of the process leading to the creation of goods and services. Goods refer to tangible assets that are produced in forehand before their actual use. Services are referred to intangibles provided at the time when customers need them.

Vinay V. Panicker [36] list out the modern day economic realities of manufacturing. These realities include the following: -

- Globalization
- International outsourcing
- Local outsourcing
- Contract manufacturing
- The trend toward the service sector
- Quality expectations
- Operation efficiency

He describes production management in terms of manufacturing, as the process of converting inputs (labour, material, money and machine etc.) to desired outputs (Goods and services). It also involves management of resources efficiently and effectively. Its process is shown in Figure 28.

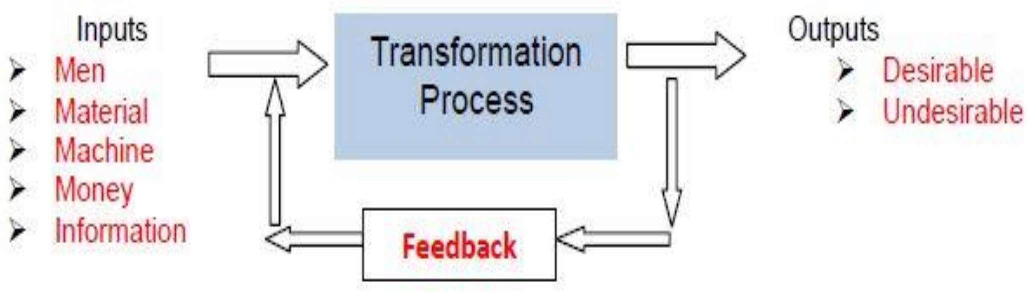


Figure 28 - Production process or Transformation process [36].

He also explains the difference between production management and operation management: -

- If it is a product-centric, then its ***production***.
- If it is a service-centric then its ***operation***.

Components of a production system: -

The two important components for a production system are: -

- **Facility** – the way factory (plant layout) and the equipment in the facility are organised.
- **Manufacturing Support System** – Procedures used to manage production, to solve technical problems and ensuring that the products are meet expected quality standards. It includes efficient equipment allocation layout and workers in the facility. The combination of workers and machines are termed as production station or production line.

Manufacturing system can be classified into three types: -

- Manual work systems
- Worker-machine system
- Automated system

For example, Worker-machine system (Figure 29) – A worker operating in a powered machine.

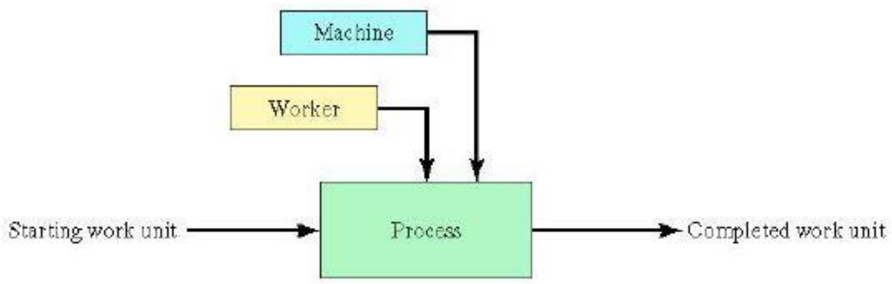


Figure 29 - Process diagram of the worker-machine system [36].

2.4.1 Phases of product development

M. Murthy et al explains [37] the various activities carried out by a different department of the organization in new product development are listed (Figure 30): -

1. Planning
- This is the zeroth phase, the output of this phase is the project mission statement, objectives and strategic plans to achieve the objective.
- The aim of this phase is to exploit emerging opportunities and select one idea for further investigation. Less than 10% of the overall ideas contribute to the final product.
2. Design
- The initial design is about creating an optimal product architecture. Product architecture is related to mapping the functional elements and their interaction with each other. It's important to understand the physical interactions of sub-assemblies and assemblies, especially for `modular´ products.
- Once that has been done, the detailing part should commence. Properties like material, dimensions, tolerance and the type of finish should be documented. These documents are later transformed in detail drawing and bill of materials, which are primary for formulating production documents.
- These design activities are iterative by nature. The more factors you consider for changes can lead to more parts to be redesigned. That's why several peer-to-peer reviews and higher-level approval on each stage of the design is key. The final stage of the design phase may have a critical design review consisting of high-level stakeholders, who verify if the design objective has been achieved.
3. Development
- It's both component and product prototype testing. Development is a term more related to creating new technologies and using it outside its usual area of usage.
- Development happens with series of tests for engineering, benchmarking or for environmental demonstration.

- Once the prototyping is finished, a range of test for the product performance is conducted like reliability, maintainability, support equipment compatibility, pre-assembly test and field test etc.
- For custom-built parts such as jigs and fixtures, development serves to verify if the desired performance is achieved as per the agreement between the client and the manufacturer. If the desired result is not achieved, it's also a good time to find solution parallel to other activities.

4. Production

- This is the hardest part as no 2 products are the same as there is always some tolerance is associated with the products manufactured. There a variety of factors for it like material, the processes used to produce, labour skills, working environment and equipment etc. The ones that most likely to influence in the current project.
- But there are several ways to control these variations and keep them to an acceptable limit. Some of them are listed below: -
    - ***Process control*** – States either the process is in-control (non-conformities within the acceptable limits) or out-control (more than an acceptable amount of non-conformities are produced). It's mostly represented through SPC (Statistical process control) charts.
    - ***Inspection and Testing*** – Inspection staring from procurement of raw material and parts outsourced from vendors with help of sampling methods. And testing of products at necessary stages of the process. Auditing of the facility also helps in achieving higher overall equipment efficiency (OEE).
    - ***Custom made a test for custom made a part*** - This applies to scenarios such as this project were specific project requires a certain type of test. For example, in this project FEA will a key test in making sure the jig can withstand a huge amount of stress and reliability factors etc.

5. Post-production

- For standard products, this phase has 2 sub-phases: Marketing and after sale support. But this doesn't apply in this project. It's a more custom-built product having its own set of post-production procedures like the analysis phase of the improvements that's been aimed at this new jig.
- Also, the cost analysis is a critical one to carry out as this project works with CNC machines it's important to know the improvement in operating cost of the project.

Pre-development		Development	Post-development	
Front-end	Design	Development	Produc-tion	Post-production

Figure 30-Phases of product development [37].

2.4.2 Principles of flexible and agile manufacturing

Flexible manufacturing system (FMS) was a huge topic interest in the early 1980s and 1990s, as it took a huge amount of time for manufacturers to understand the changing dynamics of the customer need. In this literature review about flexible manufacturing, one can understand the definition, application and its significance, all in relation with machining operation in mind, which is a key aspect of this project.

Definition: H.K. Shivanand et al. [38] gives plenty of different explanations for FMS. The one that is suitable for this project is, Flexible manufacturing system (FMS) consists of several machine tools along with parts and tool handling devices, such as robots, arranged in flexible manufacturing cells (FMC). So, that it can handle any family of parts for which it has been designed and developed.

Objective: Initial studies after FMS installation are shown the following: -

- Increased quality, machine utilization, throughput.
- Decreased lead times (A requirement for this project), Work in Progress(WIP), inventory.
- Improved Due date reliability.

Table 3 discusses in brief about the advantages and disadvantages of FMS.

Table 3 - Advantage and disadvantages of the FMS [37].

ADVANTAGE	DISADVANTAGE
Faster and improved capital utilization	Substantial pre-planning activity
Lower direct labour cost	Expensive and prone to technological problems
Lower cost/unit of output	Sophisticated manufacturing system

Application: The flowchart shown in Figure 31 shows the application of FMS in an industry.

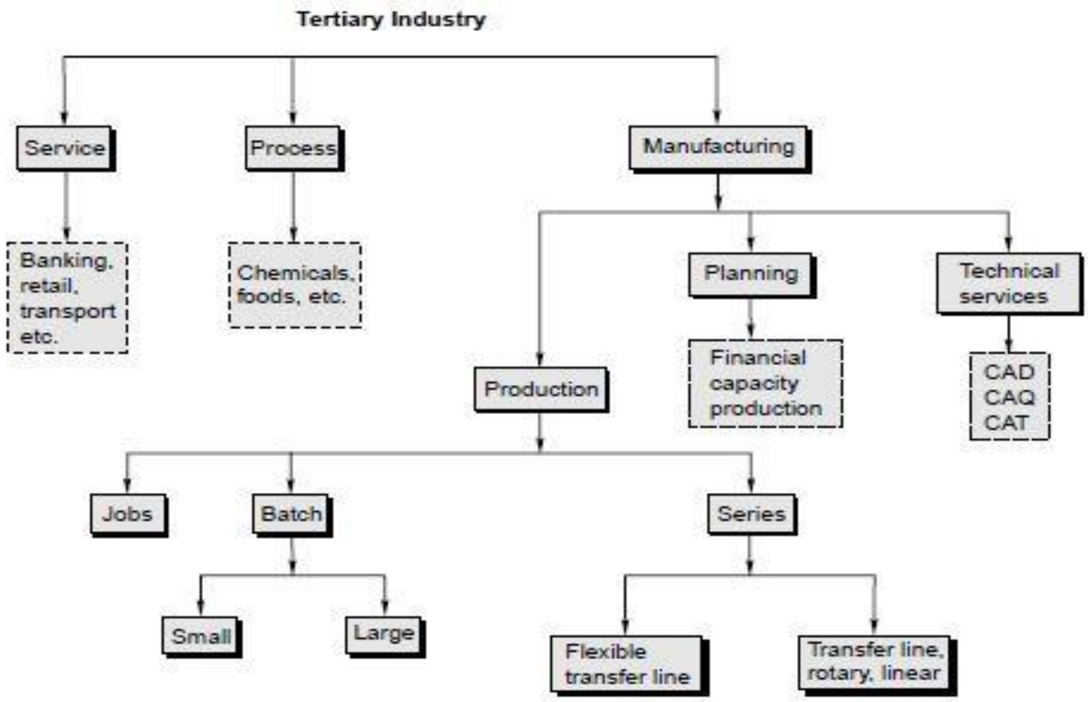


Figure 31 - FMS application in an industry [38].

The flowchart shows various tools required, factors needed for planning and types of production that is needed.

Agile manufacturing

A. Gunasekaran et al. [39] confirm that Agile manufacturing is not the same as flexible manufacturing or lean manufacturing or computer integrated manufacturing. He believes that it's an age-old misconception that they are all same. He uses examples just from a dictionary to show the differences between *Agile* is defined as quick moving, nimble and active to *flexible* defined as adaptability and versatility.

Definition: Agile manufacturing system (AMS) is a system that is capable of operating profitability in a competitive environment of continually and unpredictably changing customer opportunities [40].

(or)

A. Gunasekaran [41] has defined in another paper, Capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services. The change means able to handle variety and introduce new products quickly. He emphasis that highly customizable products are regarded as a key component of Agile manufacturing.

Important enablers of Agility:

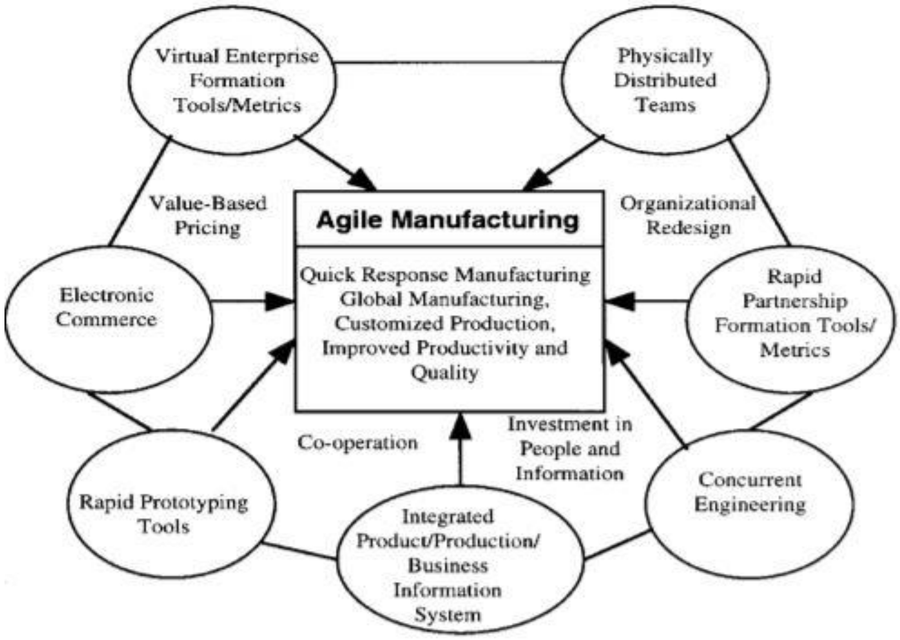


Figure 32 - Agile manufacturing enablers [41].

- **Virtual enterprise (VE)** is an opportunistic alliance of core competencies distributed among a few distinct operations within a single large company.
- **Physically distributed teams** are a new logical infrastructure support and response to reduce the lead time of the products.
- **Rapid partnership** improves the responsiveness of a firm to a changing market, requires a shared partnership between the core parts of the firm.
- **Concurrent engineering** is working of people, function and processes to work as much as possible in parallel. It includes all relevant function of a company, its supplier and its customer.
- **Integrated production/process/Business information systems** can be defined as a set of interrelated components working together to collect retrieve, process, store and disseminate information for facilitating planning, control, coordination, analysis and decision making in business and other organisations. The circle is well illustrated in Figure 32.
- **Rapid prototyping** is a primary model of a system were the end user and designer can interact and analyse. It’s done quickly and cheaply, within days or weeks.
- **E-commerce** is a computer-to-computer exchange of standard business information like P.O, invoices and bills of landing among organisations. Electronic data interchange (EDI) has lots of benefits like it helps in looking into the

customer purchase trends and help reach the customer faster and efficient than competitor.

2.4.3 SMED

P.C. Kumar [42] explains Shingo´s classical SMED approach as a systematic approach to reducing setup time. Total time corresponds to an interval of time among the last part produced a lot and the first part of the following lot (as shown in Figure 33). Developed by Shigeo Shingo in Japan in the 1960s. Single-Minute Exchange of Die tool as the name implies should try to reduce setup time to less than 10 minutes.

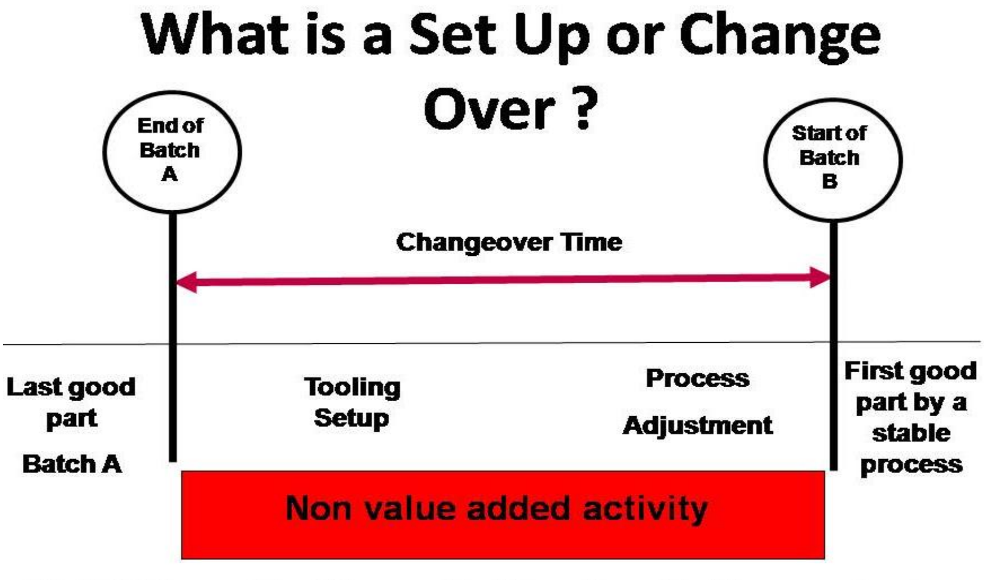


Figure 33 - Pictorial representation of change over time [43].

A. Simões et al. [44] details the four main phases of the SMED: -

- **PHASE 0** – In this general separation of *Internal activities* (activities happening while the equipment is stopped) and *External activities* (activities while the equipment is running). It's a phase that requires everyone's participation.
- **PHASE 1** – This phase refers to characterisation, organization and separation of the operation to internal and external. An important phase as most part of improvements happens here.
- **PHASE 2** - Analysis phase (of previews phase) where one verifies or restructure the categorised operation and focus should be directed towards converting internal activities to external activities. The outcome of this phase which will be the implementation of new procedures should yield a reduction in setup time.
- **PHASE 3** – In the final phase try to reduce the time of both internal and external activities. Continually improve for sustained results.

S. Imen [43] in his report has detailed 6 most common steps in SMED: -

- Map the current changeover process.
  - Time study
  - Visual Stream Mapping (VSM)
- Identify internal and external activity.
- Convert activities from internal to external setup.
  - Pre-drilled parts
  - Pre-loaded jigs
- Increase the efficiency of the remaining internal activities.
  - Use clamps instead of bolts
  - Use guide pins
  - Try eliminating adjustments
  - Develop parallel operation
- Optimize Start-up time.
  - Faster feed and drill speed if possible
  - Pneumatic or hydraulic clamps
- Reduce external activities time and increase its efficiency.
  - 5S implementation
  - Sub-contracting, if possible

2.4.4 How to collect cycle time in a production environment

Simulation expert B. Harrington [45] explains how crucial is cycle time in designing an advanced manufacturing facility. With increasing the number of cycle time comes increasing changeovers. To make things complicated responding to different product variety of the market demand, the need for changeovers keep increasing. So, he says sometimes these collection data can be difficult and can be very crucial information in designing a manufacturing facility (capacity needed). Let see one such information often used.

TAKT TIME: `Takt´ meaning pulse, set the rhythm across all the process. It's the maximum time in which a product needs to be produced in order to satisfy customer demand [46].

$$Takt\ time = \frac{Total\ avilable\ working\ time}{Customer\ demand} \tag{3}$$

S. Rahim et al. [47] highlights the key factors that influence cycle time. They are WIP, bottleneck equipment availability, throughput, reworks, other equipment availability, dispatch and setup. In order reduce higher cycle time one must overcome unnecessary waiting time, unscheduled downtime and rework.

The SMED data collection should occur by gathering process-related information, such as: -

- Observation and recording of activities and its sequence of the current changeover.
- Activities durations.
- Aspects related to activities, if any.
- Proper documentation all recorded data.
- Critical points that reduce setup procedure (effectiveness/efficiency)
- If possible, informal interview with collaborators.

2.4.5 Principles of industrial costing and payback

Customers appreciate a business that solves their know problem in manufacturing or any other aspect of the business that’s needed. But these decisions are taken based on bottom-line profitability. The payback requirement is purely based on what the business or its stakeholder´s interest. It could be 6 months or 36 months. To calculate payback one needs to know the following [48]: -

- One-time capital outlay
- Cost of installation
- Annual benefit
- Ongoing annual expense

Table 4 - Explanation of investment, return and payback using an illustration [48].

INVESTMENT	EXAMPLE	RETURNS	EXAMPLE
One-time capital outlay	Custom power or generator in the frequent power cut region.	Annual benefits	Cost of reduced downtime
(+)		(-)	
Installation	Installation cost	Ongoing annual expense	Maintenance
Net investment		***Net annual return***	

For better understanding, the concept of investment and return are explained with help of an example in Table 4 [48].

$$\text{Payback (months)} = \frac{\text{Net investment}}{\text{Net annual return}} * 12 \qquad (4)$$

2.5 Design for Six Sigma (DFSS)

The machine that changed the world [49] describes in detail the evolution and adaption of lean manufacturing in the automobile industry all around the world. Browning [50] stated that "lean is not mere minimizing, cost, cycle time or waste, lean is maximizing value". Lean can eliminate any unwanted activities or process that doesn't add value to the customer. Hence these concepts can be applied to various other areas like product design.

Womack and James [51] have cautioned readers in their paper that every reengineering or new product design should be designed with customer-centric values as the most prioritised ones. However, customers are just one of the stakeholders in a company and others like supplier, contractors, workers and shareholders do need to be considered in the product value adding service. So, it's not easy, even quality 4.0 emphasis on getting the design done at the first instance because the competition is so fierce you want to shorten the lead time from `Idea to Market´ to stay competitive.

Kibbe et al. [2] in general describe the various quality tools that could be used in different stages of the product development cycle or re-engineering. Like how value stream mapping (VSM), a visual planning technique can help in finding visible waste and some other typical lean engineering tools that can be used to improve the design process. They are Finite Element Analysis (FEA), 3D modelling and Design to Manufacturing and Assembly (DFMA). Some of these techniques are being employed in this problem addressed in this research as shown in Table 5.

Douglas et al. [52] explain the integration lean, the waste elimination philosophy with lean six sigma, the variation reduction technique. Saying that there are an array of tools and implementation play a huge role in the success factor of lean six sigma. The 7 basic quality tools are still powerful in this day age. The various phase of the DFSS is shown in Figure 34.

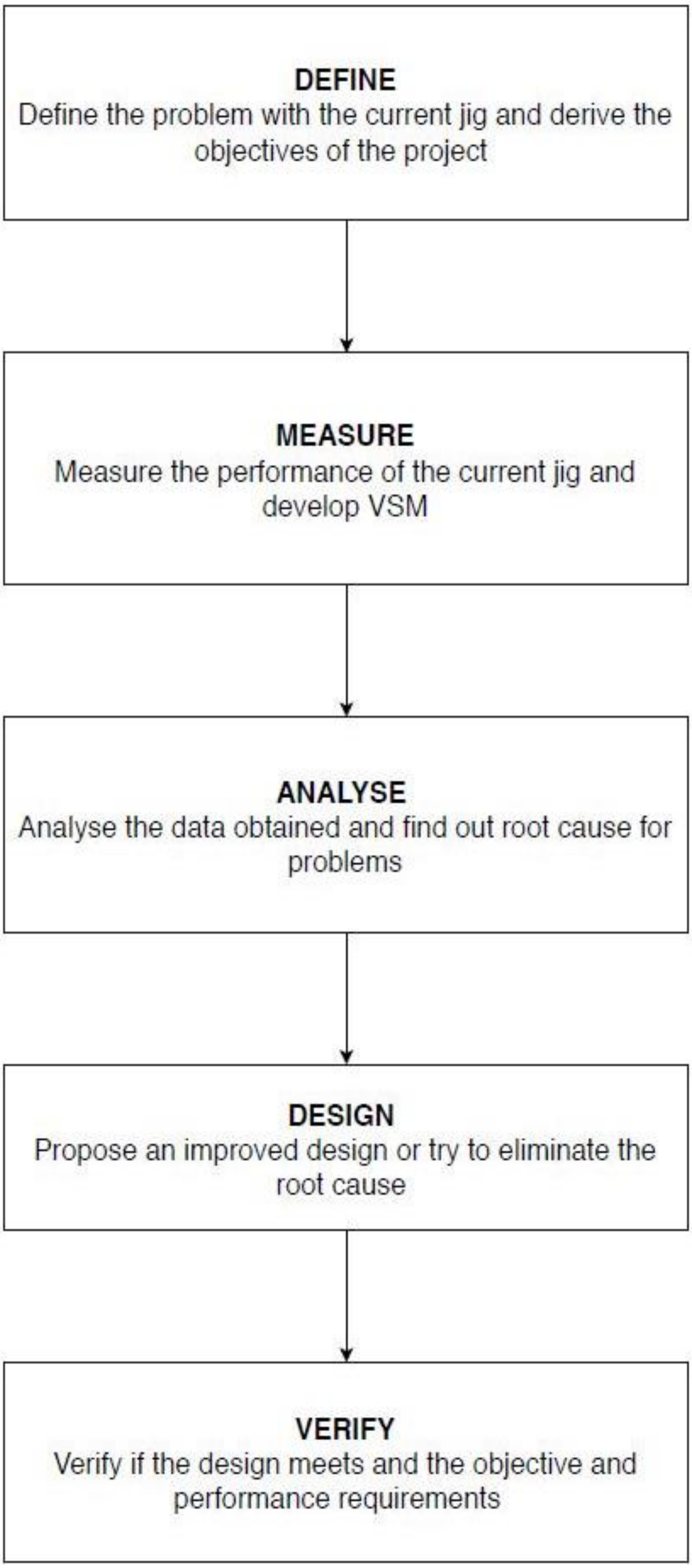


Figure 34 - The various phase of the DFSS methodology [2].

Table 5 - Tools that are used as part of the DFSS methodology [2].

TOOLS	APPLICATION
VSM	Mapping of every process step and try to identify areas for improvement.
DFMA	Designing for simplicity and manufacturability in mind.
3D CAD Modelling	Easy visualisation, easy to review for improvements and reduced inference errors.
FEA	Simulation of material stiffness, safety factoring and design optimization before manufacturing.

2.6 CNC Programming

The ever-increasing need for computerised manufacturing has created the need for skilled CNC programmers to get the required shape and accuracy. G-code or RS-274 is the most commonly used NC programming language. G-codes (Preparatory codes) and M-codes (miscellaneous function) are often called cycle codes as they refer to some action occurring on the X, Y, and Z axis of a machine tool. In this section, one will study about few basic programming systems and codes needed in this project [53].

2.6.1 Work Coordinates

A system of rectangular coordinates is a basic setup when working with CNC. There are 2 types of reference point system: -

- **Incremental –** location is always given as a distance and direction from the immediately preceding point.
- **Absolute –** Always given from a single origin point, usually fixed on the machine table. Figure 35 shown will help in differentiating between the two.

The figure also highlights how the G – Codes will be different for both the coordinate systems. The absolute system is the most preferred when most of the dimensions are known. Incremental are only used situations were multiple locations are needed to be reached in a linear space.

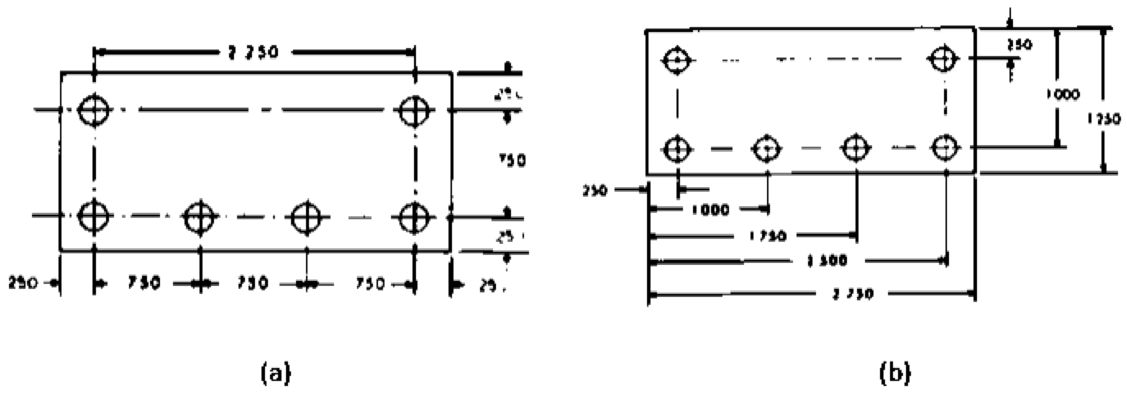


Figure 35 - (a) Workpiece dimensioned in the increased system mode (b) Absolute system mode- all dimensions are given from a known point of reference [53].

2.6.2 Positioning system

Most control units can handle both point-to-point and continuous path machining. The difference is very distinct as shown in Figure 36 but the knowledge of both the programming methods is necessary as an operator.

- **Point-to-point positioning** is used when it´s necessary to accurately locate the spindle or the workpiece mounted at one or more points to perform operations like drilling, tapping and boring.
- **Continuous path** is used in a process where there is a constant cutter-workpiece relationship is required. The cutter is in contact with one programmed point to the next with a programmed feed rate to produce the form or contour required.

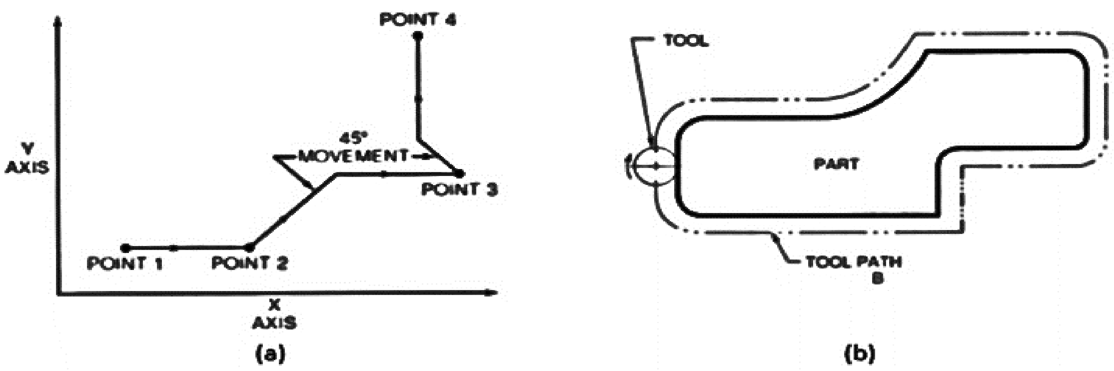


Figure 36 - (a) The path followed by point-to-point positioning on the XY axis (b) Smooth continuous contour [53].

2.6.3 Interpolation

The method by which the tool moves from one programmed point to the other is called interpolation. There are five methods of interpolation, but most controllers use only linear and circular interpolation. Helical, parabolic and cubic are used in controllers for complex shapes [53].

2.6.4 Codes

G-codes are the proprietary codes, while M codes are used for miscellaneous function and other codes such as F, S, D, A and T are used for feed rate, speed, cutter diameter offset, Optional A-axis motion command and tool number respectively [54]. G codes are usually grouped depending upon the function. The most commonly used codes are listed below in and the detailed list of codes are attached in ANNEX2.

2.6.5 Block of information

General programming ideology is in blocks, that contain 5 words. Each word is represented in the EIA standard and written on a horizontal line. All though in advanced controllers like Haas it´s not necessary to have 5 words in each block, where looping and another kind of structured programming are constantly used. An example is shown in Figure 37.

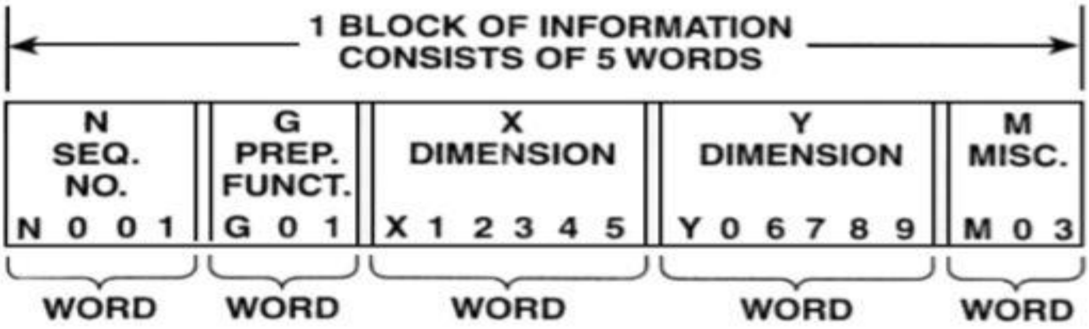


Figure 37 - A complete block with 5 words in use [55].

THESIS DEVELOPMENT

3.1 Company´s presentation

3.2 The product -Winding cone for overhead garage door

3.3 Jig Previous requirements

3.4 Brainstorming

3.5 Designing of the main components

3.6 Feasibility analysis

3.7 Jig design

3.8 Selection of materials

3.9 Validating the structure using FEM

3.10 Jig fabrication

3.11 Operation study

3.12 Modularity of the jig

3 THESIS DEVELOPMENT

This section addresses the development of the experiment from its initial stage to final output comparison.

3.1 Company's presentation

3.1.1 History

Fundwell Lda., a small-scale Aluminium and Zinc alloy die casting company. Production started in 2003 when Mr António Magalhães (Owner of Fundwell) acquired the facility in Ribeira street, Gueifães Maia. The company was rebuilt with the aim of improving production capacity and operational efficiency.

In April 2012, the company was certified for the norm NP EN ISO 9001:2008. Which shows our commitment towards continuously improving the quality of the product and gives an opportunity to stand out from the crowd.

3.1.2 Mission

Production of quality components of aluminium and Zinc alloy by Efficient die casting process.

3.1.3 Products

Fundwell´s product portfolio covers a wide range of industries and customers, among them, are automotive industry, construction, footwear industry, road safety and binding machine. The company has the truly taken advantage of the latest technologies by upgrading to the latest machines and continual process to stand out from the competition.

3.1.4 Hierarchy structure

The roles and responsibility are shown in Figure 38.

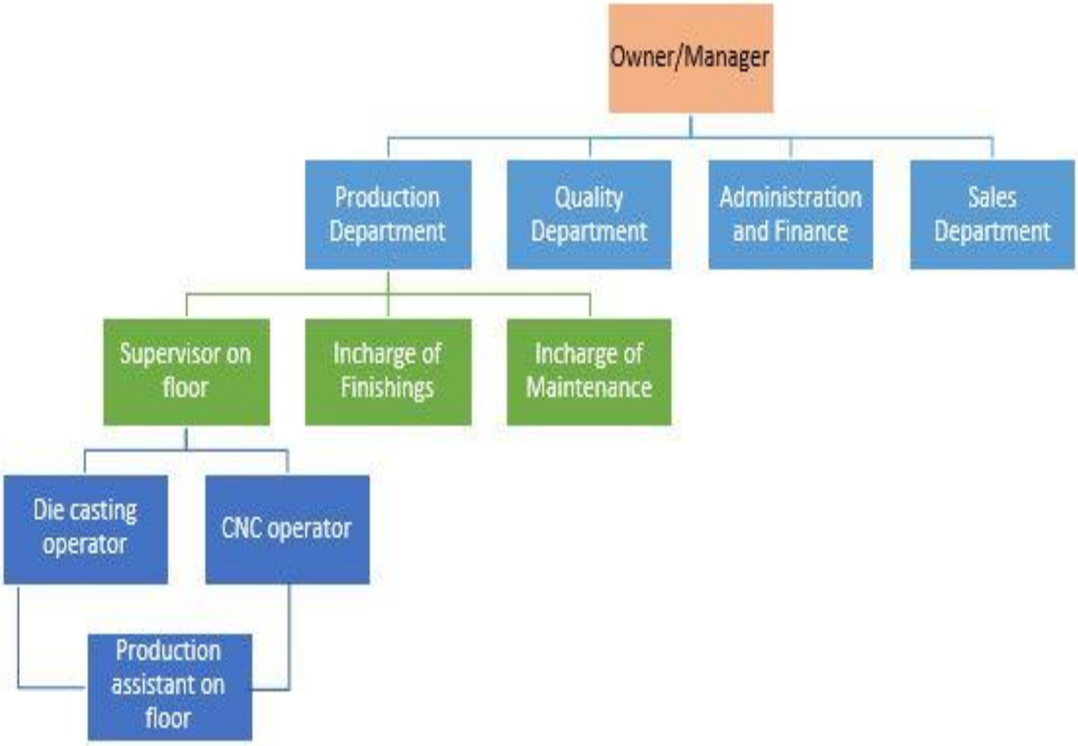


Figure 38 - Company hierarchy.

3.1.5 Quality Management System (QMS)

Objective

To document various aspects of QMS implemented to meet the requirement of NP EN ISO 9001:2015. A Quality manual is prepared and is in use in all process to exceed customer expectation.

Policy

- Committed in increasing customer and training employees to become competent in current technologies and hence generating value to the company.
- Continuous improvement of QMS and systematic reduction of nonconformities.
- Establishing a healthy relationship between various stakeholders.
- In search of a new challenging project and partnership in the best interest of the company's value generation.

Quality system structure

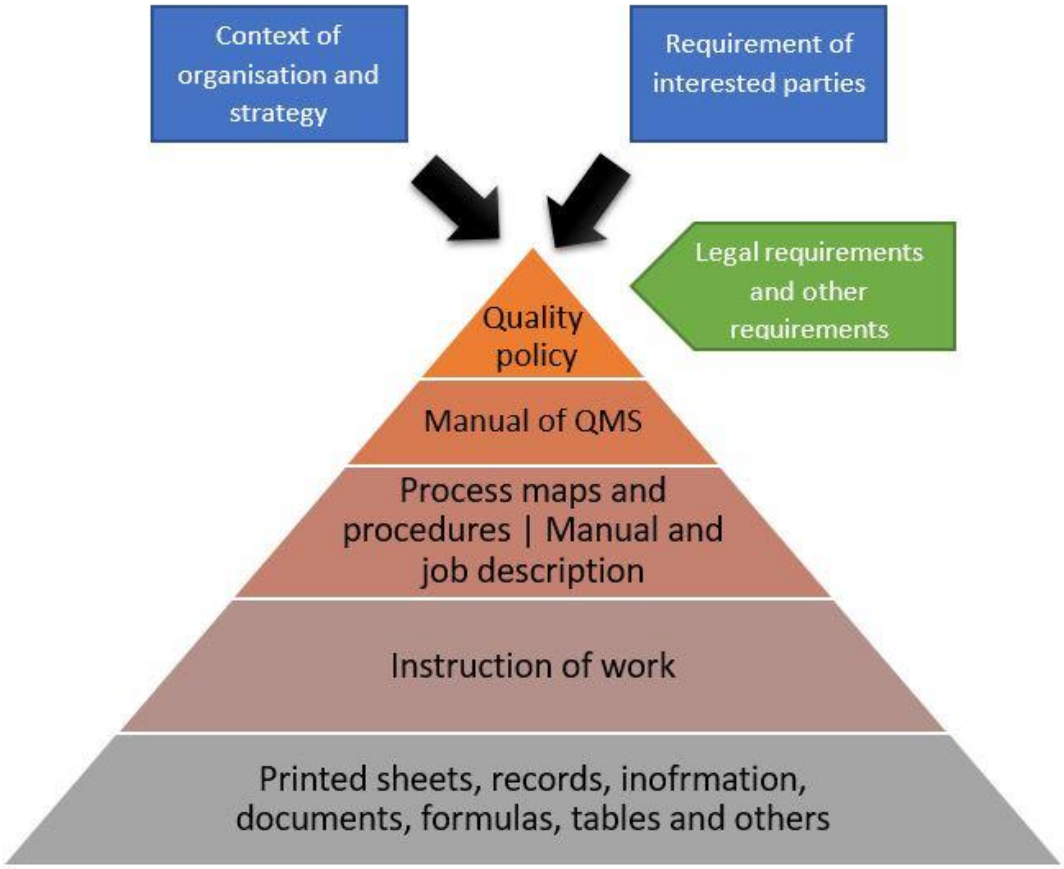


Figure 39 - QMS structure.

In Figure 39, Fundwell's documentary structure is represented, namely the Quality Manual that describes the organization's QMS, showing the application of the standard of reference to the reality of the company. There is also documented information describing the methodologies used to perform various activities and to comply with the requirements of the standard.

3.2 The product – Winding cone for overhead garage door

The part that used in this project are the winding cones used in overhead garage doors. Traditionally garage doors were made in one piece, but modern doors are made up with four or five hinged sections with roll-up or overhead doors [56]. There are six main components of a garage door: cables, drums, torsion shaft, tracks, rollers and spring (as shown in Figure 40).

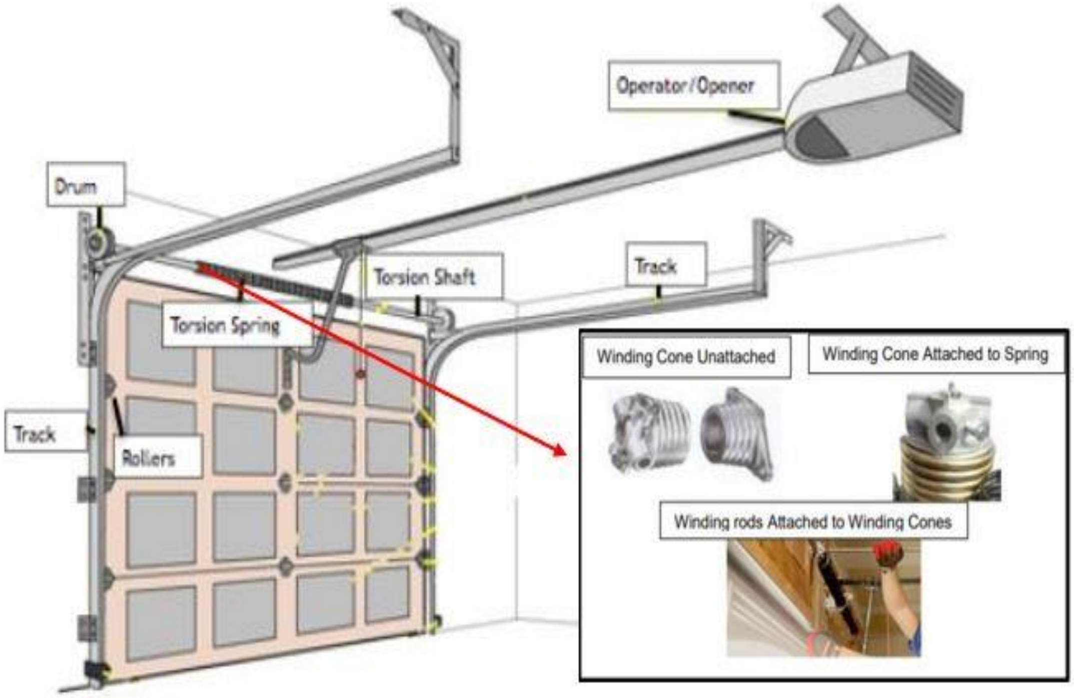


Figure 40 - Major components of an overhead garage door [57] [58].

They are available in a variety of height and width and usually weigh a few hundred kilos. The principle behind its working is a very simple one due to the torsion spring which is attached to torsion shaft. When the door Is closed, the torsion spring is under tension and the energy is stored in the wound springs does the most of the work when the door is raised [58].

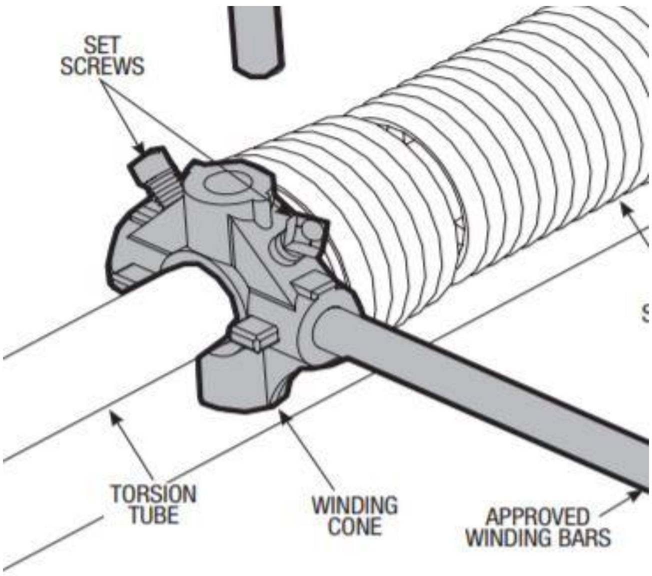


Figure 41 - Winding cone [59].

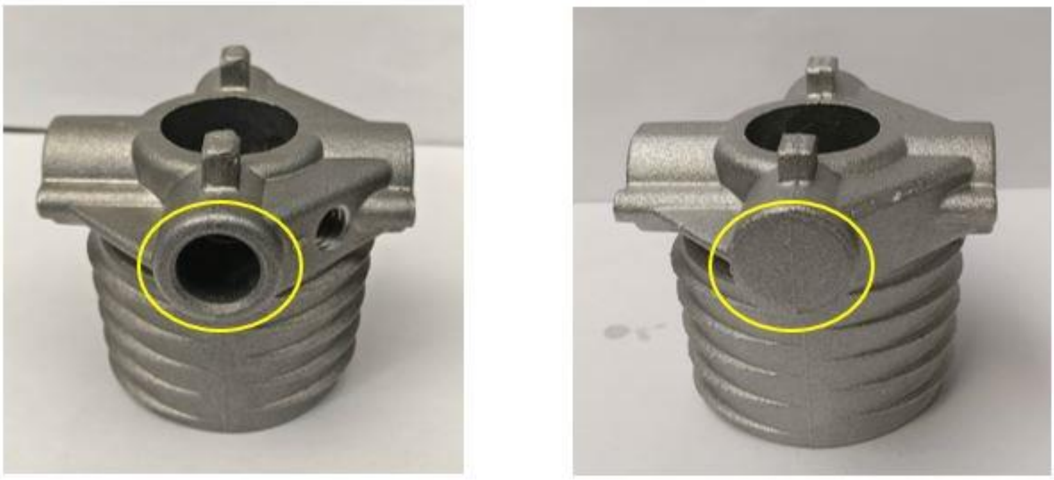
Cones are needed at the end of torsion spring for a firm attachment. So that the torque is effectively transferred to the shaft [60]. The number of 1/4th winding is specifically based on the door height. Unbalanced doors can cause serious damage to people and materials around the door as the torque and weight of the door can very dangerous to work with [59].

3.2.1 Part specification

There are two version of the product (Portuguese name: Torção 50) that are offered to various clients. They are produced using two different sets of moulds due to the requirement of the clients. The parts are identical in basic dimension but just one key difference is that one part requires an additional process of machining compared to the usual 2 processes required. In this report, they will be mentioned using the following names: -

- Winding cone_1 - The one requiring 2 process machining.
- Winding cone_2 - The one requiring 3 process machining.

In this project, initial requirements are based on the winding cone_1 but the design incorporates the needs of winding cone_2 machining process too. The pictures of the 2-version of the part are shown in Figure 42 for a better understanding of the reader.



(a) (b)

Figure 42- Two versions of the product: (a) Winding cone_1 requiring 2 processes and the hole is made by the mould itself (b) Winding cone_2 requiring 3 processes and the hole closed highlighted in the yellow circle

Also, winding cone_2 is in the process of being discontinued and negotiations are in place with the customer. So, the data’s and information provided in this section are for a better understanding about the product variety and the thinking behind the designing the jig. As it´s necessary to understand the complete history of the part, demand and its forecast.

3.2.2 Part diagrams

In this section detailed view of the part geometry and views are shown in Figure 43.

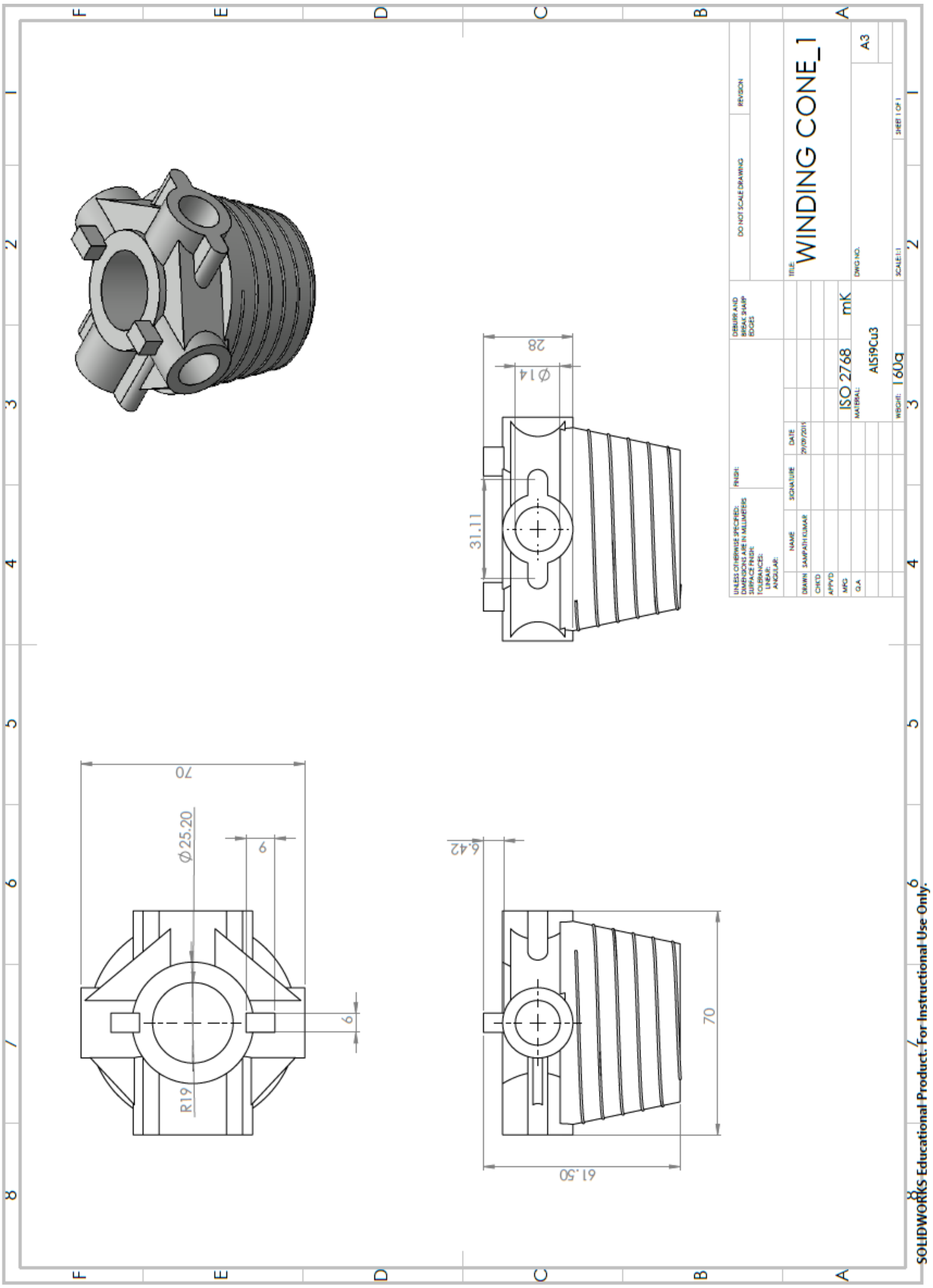


Figure 43 - SolidWorks diagram with a dimension of the part - Winding cone_1.

In Figure 44 the front, top and the right view of the part is shown. This how the part arrives to the machining centre and for the rest of the report this will be the reference regarding which view is represented to the reader.

(a) (b) (c)

Figure 44 - (a) Front view (b) Top view (c) Right view.

3.2.3 Part demand and forecast

The key part about forecasting is that it helps in managing the inventory and in turn, helps to satisfy the needs of the customers better. This applies in this part too; the order pattern is key in planning the production.

When analysing the demand data from 2015 till August of 2018, it shows that there is a positive linear curve with an expected demand for 2019 of Approximately more than 87000 units as shown in Figure 45 and Table 6.

Table 6 - History of the part sales and its forecast for 2019.

PART TYPE	YEAR					
	2015	2016	2017	2018*	Projected for 2018	2019
Winding Cone_1	60400	62000	34752	51982	69309	67950
Winding Cone_2	7744	7770	15598	13875	18500	23660
Total parts	68144	69770	50350	65857	87809	**87045**
***2018* -** Till August sales figures*						

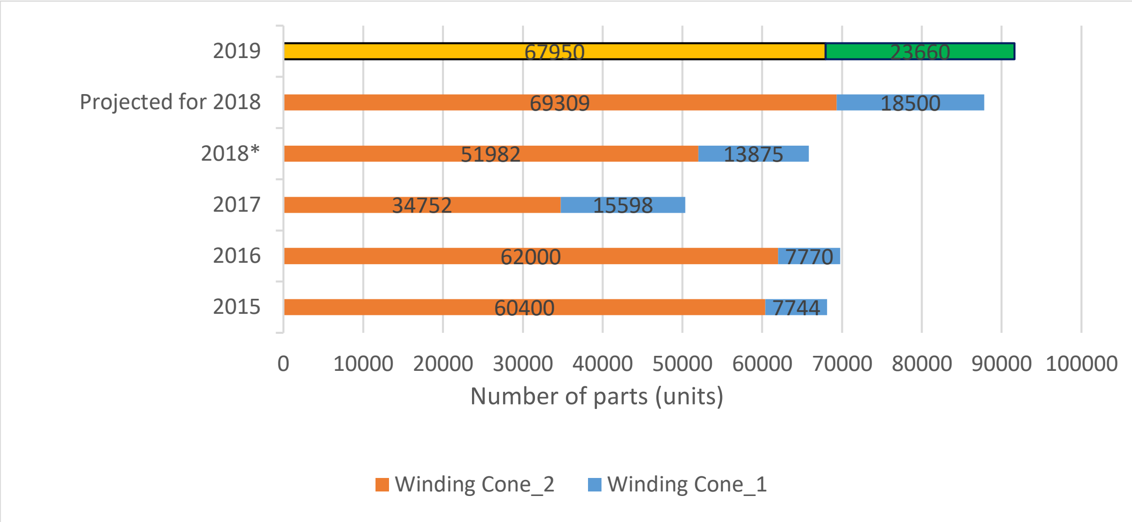


Figure 45 – Comparison chart for the part past sales versus a forecast for 2019.

To be prepared for the expected demand of 87045 parts in 2019, the production cycle time must be increased. That's exactly one of the objectives of the project. This can be shown using another performance metric called takt time as mentioned in Table 7.

Table 7 - Takt time based on the forecast.

	DEMAND	TOTAL AVAILABLE TIME	TAKT TIME
	(Units)	(mins/year)	(mins/Part)
For 2017	50350	229680	4.6
For 2018 (based on till august demand)	87809	229680	2.6
For 2019 (expected)	87045	229680	2.6

Total Available time - Assuming 14.5 hours a day x 22 days/ month x 12 months/ year

Soon every part needs to have at almost 43% faster production cycle than the previous year as suggested from the Table 7. So, in this project, the machining process is subjected to possible improvement. The idea is to reduce the machining time per part and hence improving the overall process efficiency and machine availability.

3.2.4 The Question – How to get to our objective?

Let´s put this question in a mathematical form so readers of all age could understand.

Assumption:

I. In this study, use one operator and one machine is in use at all time.
II. One caters to the same demand before and after improvement.

Table 8 - Variable of initialization with description.

VARIABLE	DESCRIPTION	UNITS
X	Number of units produced per hour	Units /hr
C	Cost of operation per hour (labour cost, energy, etc)	Euros/hr
D	Expected demand	Units
t	Total time required for an order to produced	Hours
Tc	The total cost incurred for an order	Euros
Non-negativity constraint as X, C, D, T, Tc ∈ ℝ		

So, the current production time required to produce for the given demand is,

$$t = \frac{D}{X} \text{ (Hours)} \qquad - \qquad (5)$$

The total cost of the order,

$$Tc = t * C \text{ (Euros)} \qquad - \qquad (6)$$

One of the objectives of continuous improvement is to reduce waste (time or material or process) and therefore reducing overall cost. From equation 2 it´s quite clear that one needs to reduce at least one of the total time to produce `t´ or cost of operation `C´ to bring down the overall cost `Tc´ for the same demand `D´.

Actions needed for reduction:

To increase the number of parts produced in an hour and express `X´ like the following,

$$X_{(NEW)} = A + X \text{ (Units)} \qquad - \qquad (7)$$

Where `A´ a positive integer number (Units). So, if one can make `A´ greater than zero then that will, in turn reduce the `t´ - time required to produce the order and the equation will become,

$$t(\downarrow) = \frac{D}{A\,(\uparrow) + X} \text{ (Hours)} \qquad - \qquad (8)$$

So, if `A´ increase `t´ automatically decreases in turn, reducing overall cost as per equation 2.

Action required:

To achieve the objective, one needs to increase the capacity of the parts machined per cycle, by making a jig that has a holding capacity of more than 8.

3.2.5 Operations needed in each part

The operations needed in the parts are for 2 important functions: Firstly, a hole and thread for tightening screws and secondly bigger drill used for winding the spring. A detailed understanding is shown in Figure 41. The list of operations, a tool with their dimension and lengths are mentioned in Table 9.

Table 9 - Tools and operations used in the machining process the parts: Winding cone_1 and Winding cone_2.

TOOL NUMBER	OPERATION TYPE	TOOL USED	DIAMETER (mm)	BUILT IN TOOL LENGTH (mm)	WINDING CONE _1	WINDING CONE _2
#1	Drilling	Spike Ø12mm with chamfer 45º	Ø8	56,70	✔	✔
#2	Thread	Male	3/8 UNC 16	66,21	✔	✔
#3	Drilling	Straight drill	Ø14	81,00	✘	✔

As seen in Table 9, the operations used in the two variations of the part. An important thing to note is the built-in tool length. As this parameter is kept as a standard one, so whenever a tool breaks. It´s required to be replaced with the exact length or else it could cause defects while machining. This table also highlights the design language that's needed to improve.

3.2.6 Accuracy requirements

The accuracy requirements for the part varies for different stages of the production process. But in this section importance is given only to the customer machining requirements of the process. These accuracy requirements are discussed in the later section of writing CNC codes for the new jig. The two tests that are after the machining process based on the sampling method are listed in Table 10

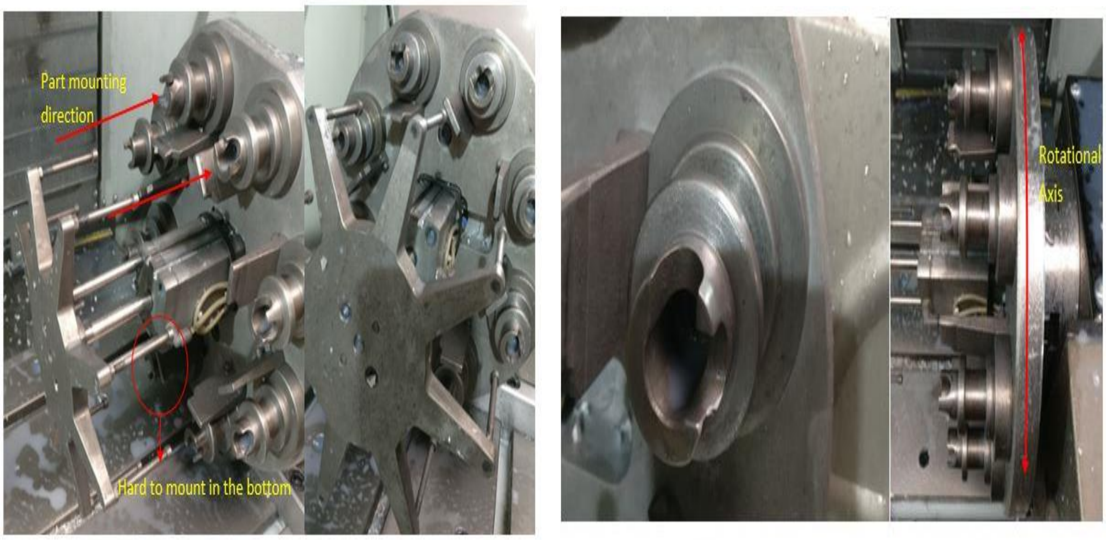
From this checks that are done, the information that's derived for the design of the new jig is that holding of the part should be tight enough that it doesn't vibrate too much to cause variations. Also, free enough to unload the parts quickly as possible. It´s going to be a very important factor to reduce defects and setup times.

Table 10 - Tools used to check the accuracy of the machining holes.

TEST NUMBER	TOOL USED	TEST DESCRIPTION
#1		• The test screw is used to check the fit of holing and taping operation. • Failed to screw fully the part is rejected
#2		• Used to check the fit of the Ø14mm hole drilled. • If it fails to enter the hole till the end, the part is rejected.

3.3 Jig previous situation

The previous jig had the capability of machining 8 parts at a time and was circular in shape. For analysing the various feature of the jig, one will use a similar tool to SWOT analysis but without the `T- Threat´ in it called as SWO analysis. Hence, it´s not the traditional SWOT analysis. It´s tailor-made for analysing designs. Shown in Figure 46 and Table 11 are few of the images of the previous jig used for machining Winding Cone_1 and critical analysis of the jig features.



(a) (b) (c)

Figure 46 - (a) Mounting direction and view of the old jig (b) Closed up view of the part holder (c) Rotational axis of the jig.

Table 11 - SWO analysis of the previous jig.

STRENGTH	WEAKNESS
• A very compact jig and requires a small area for storage. • Takes little space in the CNC table. Hence, allows the use of vice for machining. • Requires only one person to setup and its quick to setup. • Can be used for both Winding Cone_1 and Winding Cone_2 without any modification.	• High chance of loading the part in the wrong orientation. • Requires a lot of training, concentration and checking in loading the part. • Doesn't use the full lenght of the table. • Higher tool air time and coding are very hard especially, for this process. • Not the strongest of clamping using only 1 pneumatic cylinder.

OPPORTUNITY
• To improve the ergonomics of loading and unloading the parts. • Increase the capacity of parts to more than 8 with a different basic shape. • If possible, make a modular jig.

One of the main problems that's quite visually seen when the jig is at work is that the tool airtime is very high for the drilling and tapping operation due to the circular shape of the jig. It´s explained in Figure 47, and during a cycle, several of this movement is very unproductive.

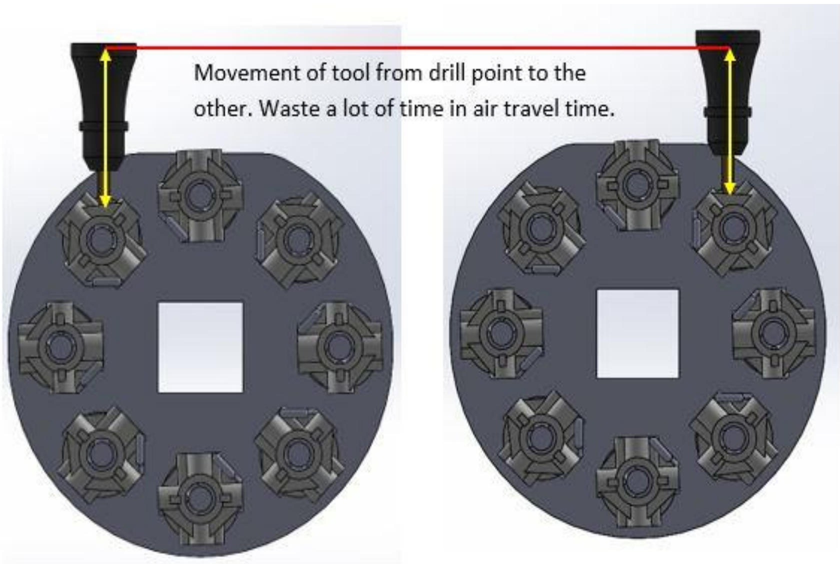


Figure 47 - Illustration of how the drill tool travels from one-point o the next one.

3.3.1 Collecting setup times of current jig

The current jig´s cycle time was collected for 10 continuous cycles. Each cycle time consists of the machining, loading, unloading and cleaning time. And from this is where one uses DFSS (Section 2.5) to start defining the project requirements and analysing the current jig. The study will continue to various other section depending upon the tools that have been used and finally compare with the final product and verify if one has achieved our objectives.

To apply Design for Six Sigma (DFSS) one can define the objectives of process steps using the DMADV approach. Other tools can also be used in these frameworks of analysis depending upon the problem at hand. Each step of the DMADV are discussed below: -

Define: The current design on the jig, one can mount 8 parts per cycle and it takes about an average of 179 seconds of total cycle time. The existing design is a fixed jig model with high loading and unloading time, which Is about 50 seconds on average as shown in Table 12.

Table 12 - Sample cycle times collected from the previous jig.

SAMPLE NUMBER	TOTAL CYCLE TIME (min)	TOTAL CYCLE TIME (s)
1	03:00.6	180.6
2	02:45.6	165.6
3	03:01.4	181.4
4	02:56.7	176.7
5	03:02.1	182.1
6	03:06.4	186.4
7	03:00.4	180.4
8	02:58.7	178.7
9	03:03.2	183.2
10	02:59.7	179.7
	Average	**179.48**

Hence 1/4th of the machining (value-adding process) time is wasted in setups. So, the following could be the objectives of the design:

1. Reduce the setup time – less than 50 seconds.
2. Increase productivity – more than 8 parts per cycle.
3. Reduce overall cost – bring down the cost per part.

Measure: The current design, which is a circular one (as shown in Figure 46) with a radial length of almost 160 mm (the maximum radius possible for this table setup). It uses a stainless-steel design for high strength and rigidity. It uses a pneumatic clamp and supports to counter any movement across the 12 degrees of freedom. It's possible to see through VSM a six-sigma tool to map the current process and look for improvements to implement in the new design or remove non-value adding process. For this part, one must list out each step of the process with timings, opportunities for improvement or not and Key Performance Indicator (KPI) for improvement that's visible from VSM process. Table 13 shows the summary of VSM in Figure 48.

Analyse: Basically, from the timings that have been measured it can be categorised as value added tasks (in seconds) and non-value-added tasks (in seconds). Process Cycle Efficiency (PCE) is a six-sigma metric to analyse and improve processes. In our current design, one can see only the machining process of 129 seconds adds value to the total process time of 179 seconds. From this, one can calculate PCE by us the formula below,

$$PCE = \frac{Value\ added\ time}{Total\ process\ time}\ x\ 100$$

So, that gives as a PCE value of 72.06%. The results show that the current process is a good one but there are chances for improvement. Like a modular design would significantly eliminate the non-value-added time in the process or simplify the activities in the process to reduce non-value-added time. listed in Table 14 are few important metrics to consider going forward in the project.

Table 13 - Steps involved in the process with their time and finding areas of opportunities to improve.

PROCESS STEP	AVG. TIMING OF THE OPERATIONS (s)	MACHINE RUNNING, YES OR NO?	OPPORTUNITY FOR IMPROVEMENT, YES OR NO?	WHAT COULD BE IMPROVED HERE?
LOADING	20	No	Yes	Faster Procedure/ Modular Design
ADJUSTMENT (KNOCKING)	5	No	Maybe	Could Be Faster with Modular Design
CLOSING DOOR AND STARTING MACHINE	3	No	No	-
MACHINING	129	Yes	Maybe	Reduce Tool Change Time Per Part and Optimize G-Code
CLEAN THE EARLIER MACHINED PART *	60	Yes	Not Important	-
ARRANGE THE NEXT SET OF PARTS *	30	Yes	Not Important	-
WAITING *	39	Yes	Not Important	-
UNLOADING	17	No	Yes	Faster Procedure/ Modular Design
CLEANING THE JIG SET FOR THE NEXT CYCLE	5	No	Yes	Faster Procedure/ Design that doesn't require cleaning.

Table 14 - Important metric for design consideration after the analyse phase.

Total production capacity per day {(14.5 hours per day of production possible x 60 minutes *60 seconds/ current cycle time) x 8}	2320 Parts / day
Setup time	50 sec
Cycle time per part	24.08 sec
Time per tool change	1.6 sec
Chip to chip time	2.2 sec

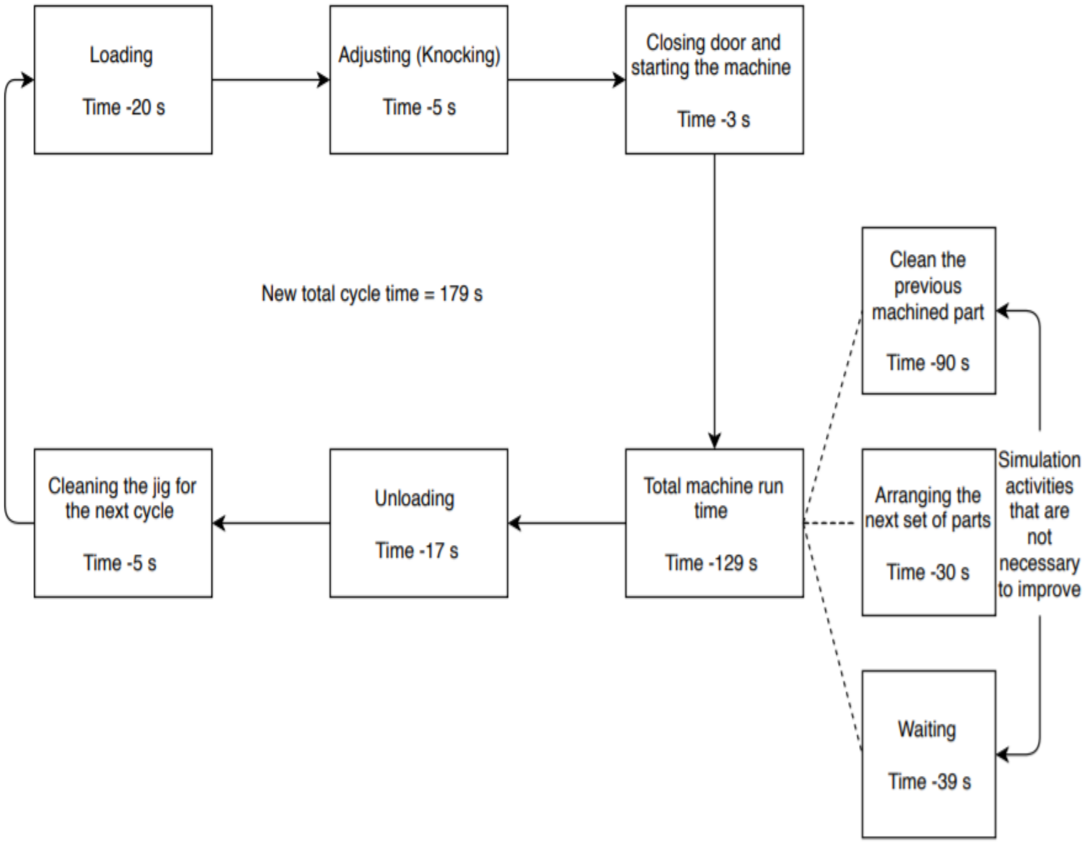


Figure 48 - Visual stream mapping (VSM) of the entire machining process.

Various other design consideration like the ergonomics, weight and cost was also analysed based on the current design. It was quite evident that it was not possible to increase the parts per cycle with changing the basic shape to the jig.

3.3.2 General requirements of the project

The general requirements or can be called as goals set to be achieved at the end of the project are already established in previous sections. But listed below are the collective form of all constraints to consider in the design and manufacturing of the jig: -

- To create a jig with machining capacity of more than 8 parts per cycle. Preferably with 10 or 12 parts per cycle, ultimately reducing the cycle time per part.
- Trying to accommodate a design that uses the total available length of the machining table.
- Design that minimizes tool travel time (optimized tool travel).
- Try to accommodate better ergonomics for the operator to load and unload the parts in and from the jig respectively.
- A modular or multi-functional jig that accommodates future projects.
- Choosing materials and design that would maximize the in-house production of the jig and reduce cost.

3.4 Brainstorming

The idea of individual brainstorming this project was due to the nature of the work of an intern. The procedure in this project would be trying to achieve the general requirements as effectively as possible with the minimal used resource. Most of part of the brainstorming involved in the design of the jig were each design idea is presented to the person in charge. From where either improvement of the design is requested, or the design is deemed unfeasible with current requirements. But the general philosophy of each design iteration was based on the design phase of the DFSS approach as mentioned in sections to follow: -

DESIGN: *This phase is an iterative phase with constantly tweaking up the design until all the parameters are satisfied. So, it like a loop, you're not done until the designs meet the objective. In this case, we had a systematic approach by making a flowchart (*Figure 49*), which paves its way to the desired design.*

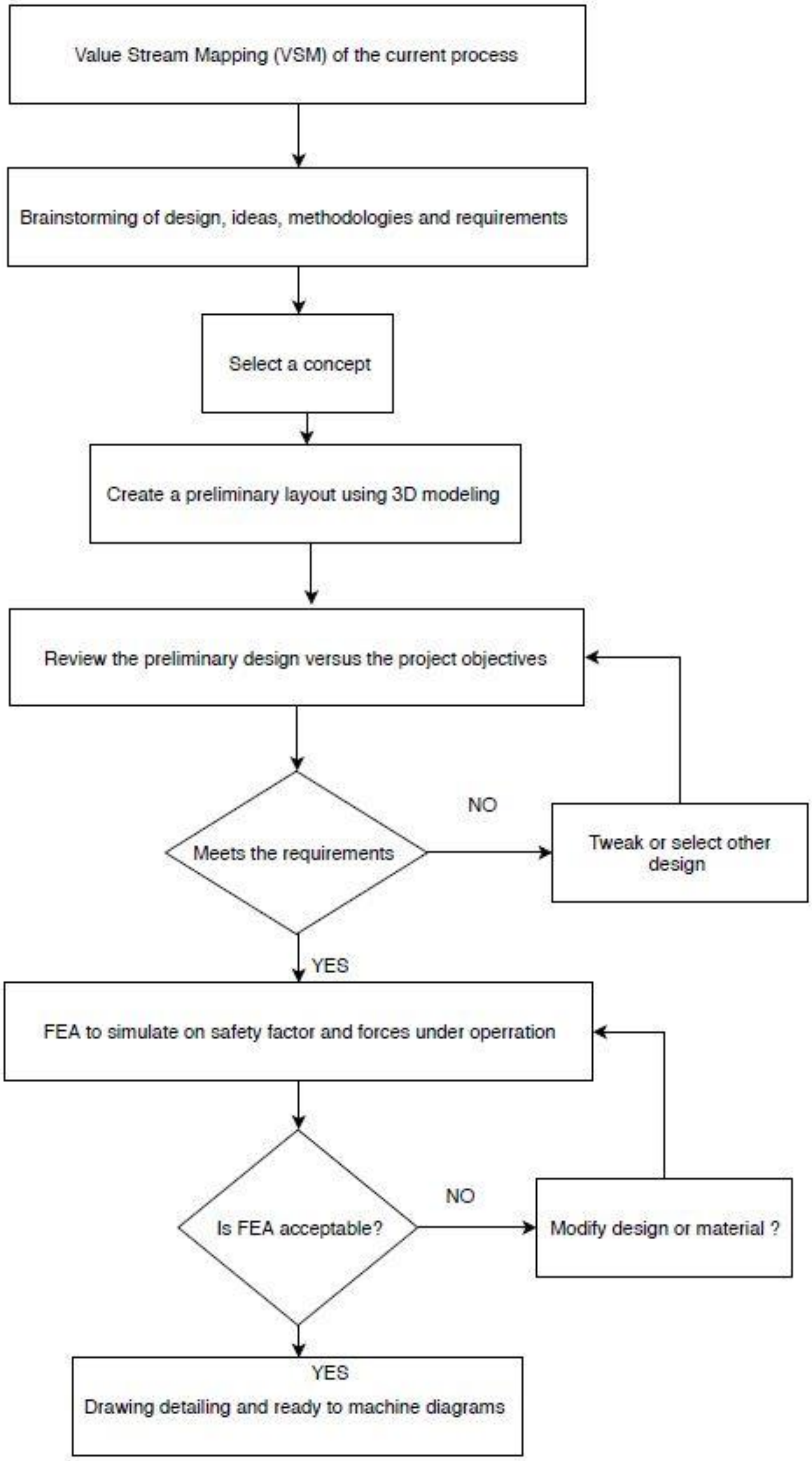


Figure 49 - Design path followed represented in a flowchart.

3.4.1 Main ideas

In the sections to follow, various designs of this brainstorming session are included and analysed using a simple analysis like SWOT (Strength, weakness, opportunity and threat). Its analysis simplifies and presents the reader only with critical information required. SWOT helps in identifying the strength and weakness of a business based on its internal factor and opportunities and threats it may face by an external factor [61]. Although SWOT is primarily used in business, it's also possible to represent the advantages and disadvantages of a design too.

But in this project, it will be used as just SWO (Strength, weakness and opportunity) analysis. *The **threat*** is something that wouldn't coincide in analysing a design. *The threat* is more seen as a weakness or an opportunity.

Design 1

The first design idea was based on the current jig in use. Instead of circle tried a rhombus-like a base plate to mount the part with similar holding mould as shown in Figure 50.

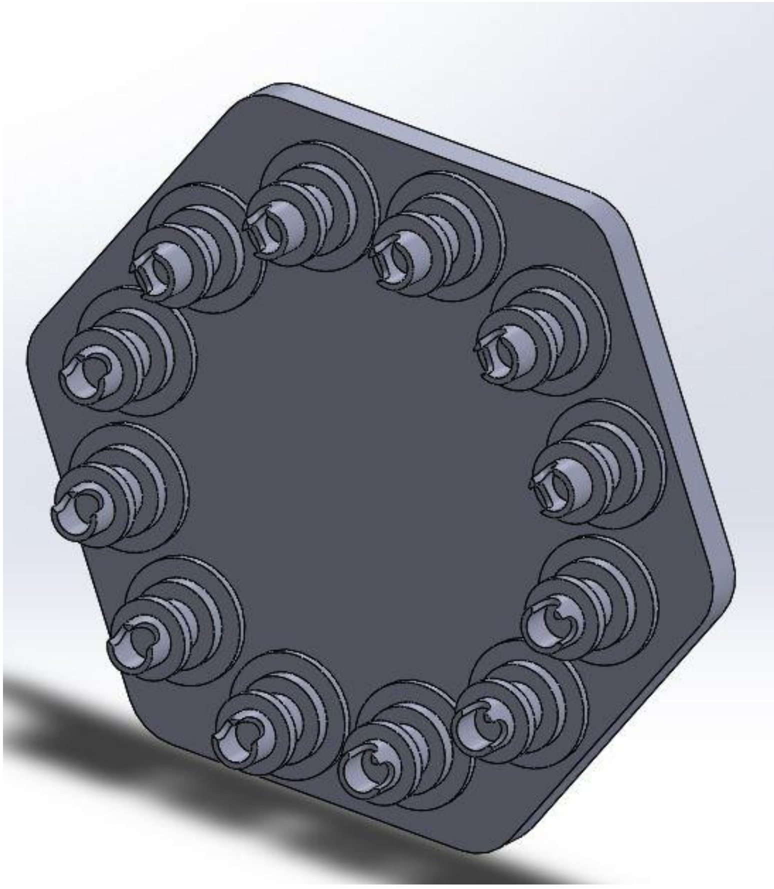


Figure 50 - Design 1-Rhombus shaped.

The critical analysis of the jig is discussed in Table 15.

Table 15 - SWO Analysis for design 1.

STRENGTH	WEAKNESS
• Compact design • Can work in current table setup and doesn't require any additional supports. • The overall weight of just 8 kgs.	• The height of the plate at is the maximum point is approximately 391mm, which is more than the maximum diameter constraint of 320mm. • Part will be too closely placed. • Looks like the old jig in some ways. • Part holding mould is very bulky.

OPPORTUNITY
• To make sure one uses a horizontal design to reduce tool travel time and increase part capacity. • Make sure plate rotating axis diameter is less than 320mm. • Maybe use a different type of design for moulds that hold the part.

Design 2

In this design, the idea was to use a similar part mould being mounted on a rectangular plate. And try to find a good spacing between 2 parts (as shown in Figure 51) as space was tight between parts in the previous design.

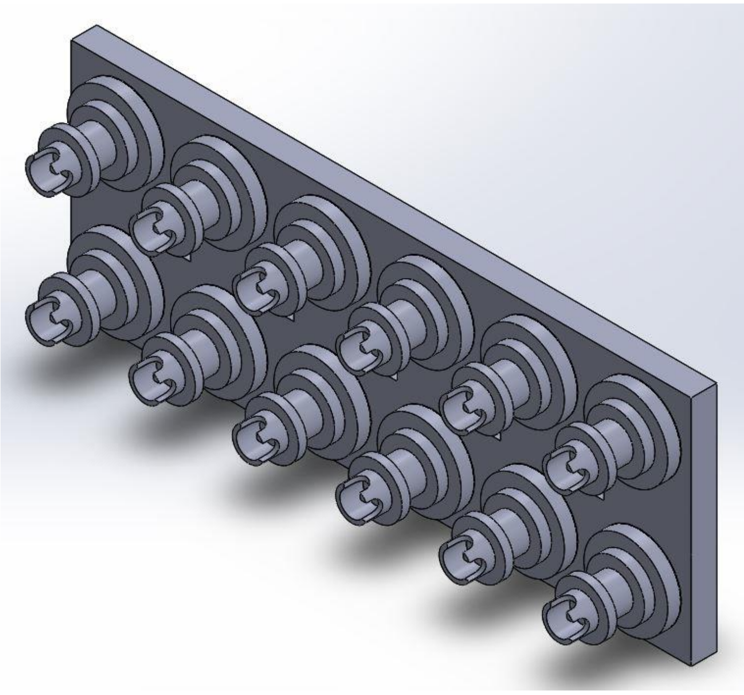


Figure 51 - Design 2-Rectangular plate approach

The critical analysis of the jig is discussed in Table 16.

Table 16 - SWO Analysis for design 2.

STRENGTH	WEAKNESS
• Still a compact design at 480 mm in length considering X-axis table space available. • Existing mould can be used to hold parts.	• Need supporting structure on the side to rotate. • Clamping could be harder and could an inherence in operation. • Need a resting surface for the part be held on.

OPPORTUNITY
• To keep in mind clamping position and try different types of clamping devices. • Continue working with rectangular design. • To make an improved part holding mould.

Design 3

This design is more of an idea for the holding mould of the part than for the jig. After the previous design, it accrued that the holding mould needs to be smaller to counter the congestion caused by the existing mould as shown in Figure 52. The runner gate cuts on the top of the part help in providing the hold.

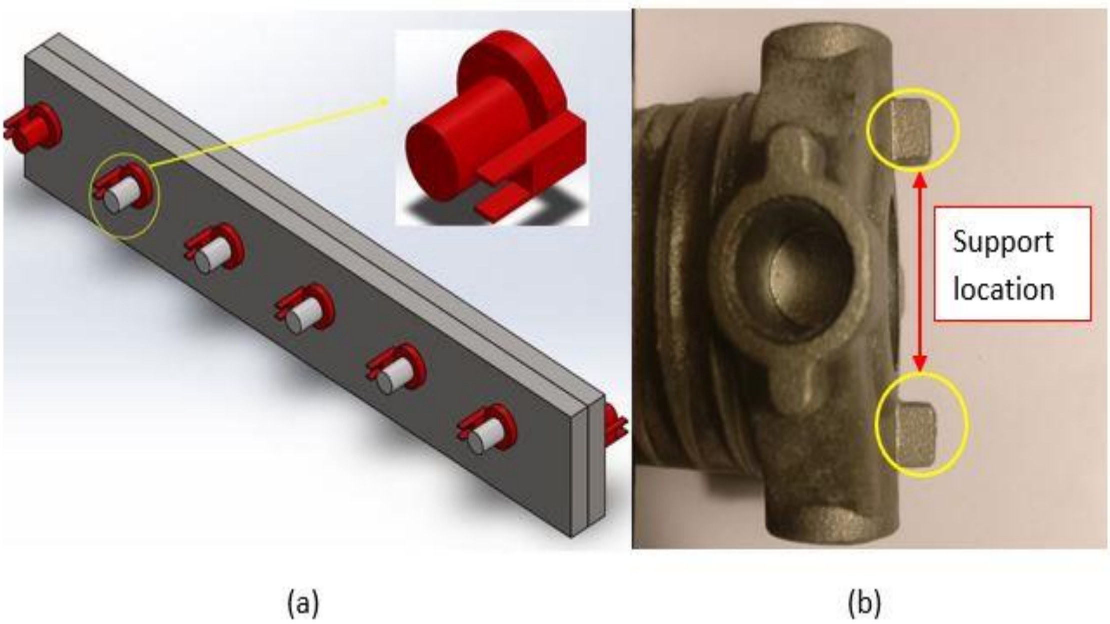


Figure 52 - (a) Design 3 (b) Finding the support location to rest on the jig.

The critical analysis of the jig is discussed in Table 17. The location of support point was finalised in this design as it is small enough compared to the previous design.

Table 17 - SWO Analysis for design 3.

STRENGTH	WEAKNESS
• Improved design of the holding mould is compact and weighs less at 1/10th of the previous design. • Overall jig design has also shelled out half of its weight from the previous ones. • Supporting devices needed should be less heavy.	• Harder to clamp with 2 faces. • New holding moulds not as strong as the previous design.
OPPORTUNITY	
• With the plates getting lighter in each iteration, could try for a modular setup.	

Design 4

This design is based on the Haas quick change cube which is a great setup for milling cubical parts as shown in Figure 53. But it had to be clamped individually. So, in this design trying a way to load, unload and clamp the part was a big challenge.

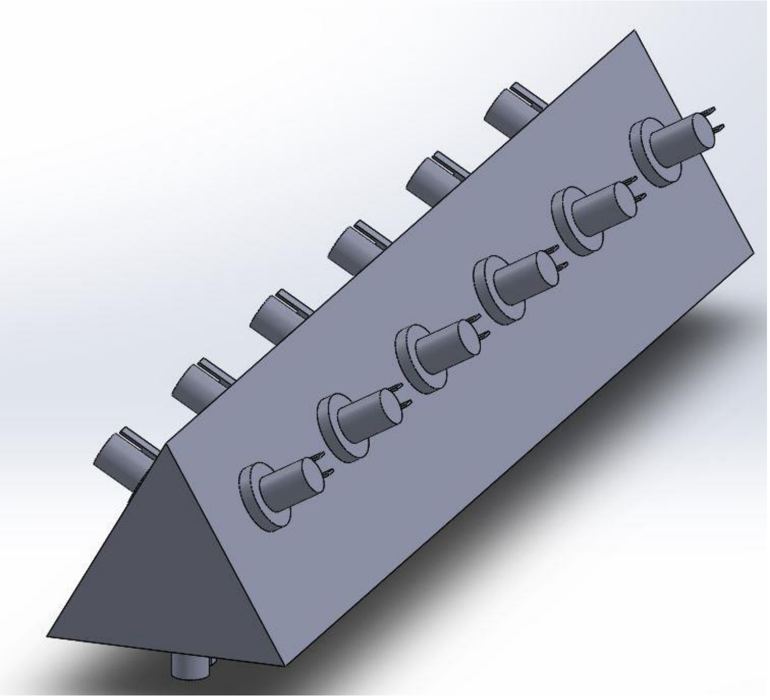


Figure 53 - Design 4-Triangle design.

The critical analysis of the triangular jig is discussed in Table 18.

Table 18 - SWO Analysis for design 4.

STRENGTH	WEAKNESS
• Could clamp more than 24 parts depending upon the length of the triangular rod. • It achieved the same amount of weight like the previous design after shell feature but for more products.	• Again, clamping is very hard in these kinds of shape. • Additional supports are needed for clamping. • Modularity could be an issue considering ergonomics.
OPPORTUNITY	
• Some designs were handles for modularity and hole pins for fixed design need to be employed for ergonomics. • Consider using shell option for the holding surfaces.	

Design 5

This design is worked with some of the references taken from the jigs that in use in various other parts manufactured in the company. The essential idea is that a plate is mounted on the base plate to provide space for actuators and rotation A-axis.

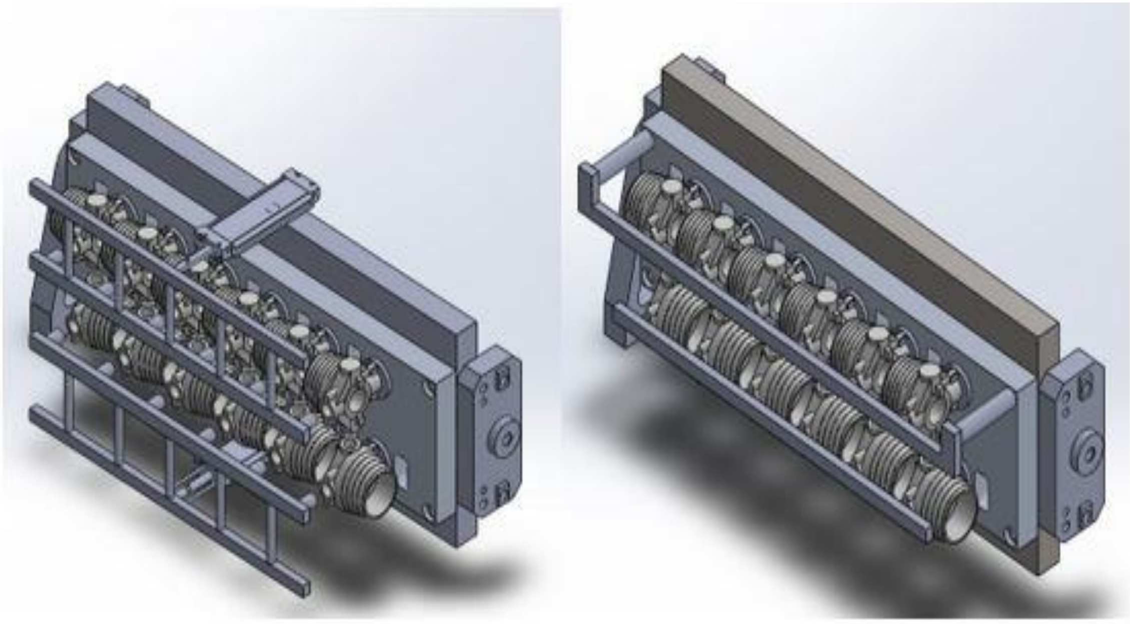


Figure 54 - Design 5.

The critical analysis of the two jigs mentioned above is discussed in Table 19.

Table 19 - SWO Analysis for design 5.

STRENGTH	WEAKNESS
• Meets almost all the design specification. • This design can be adapted to share parts of the similarly existing jig.	• Clamping rods could be in the way while loading and unloading. • Very tight tolerances for drills to work with since the actuators are better used at the top. • Heavy overall jig.

OPPORTUNITY
• Try to design clamping modules that are more agronomical to interact. • Use of much stronger clamping devices as it must withstand the parts and the plate.

Design 6

In this design, the idea was to use swing clamps that go on the side of the plate making it free from interacting with the spindle and at the same time hold both the plate and part together as shown in Figure 55. It could be said that it’s the most efficient design, but one must look at the technical and financial feasibility of the project also.

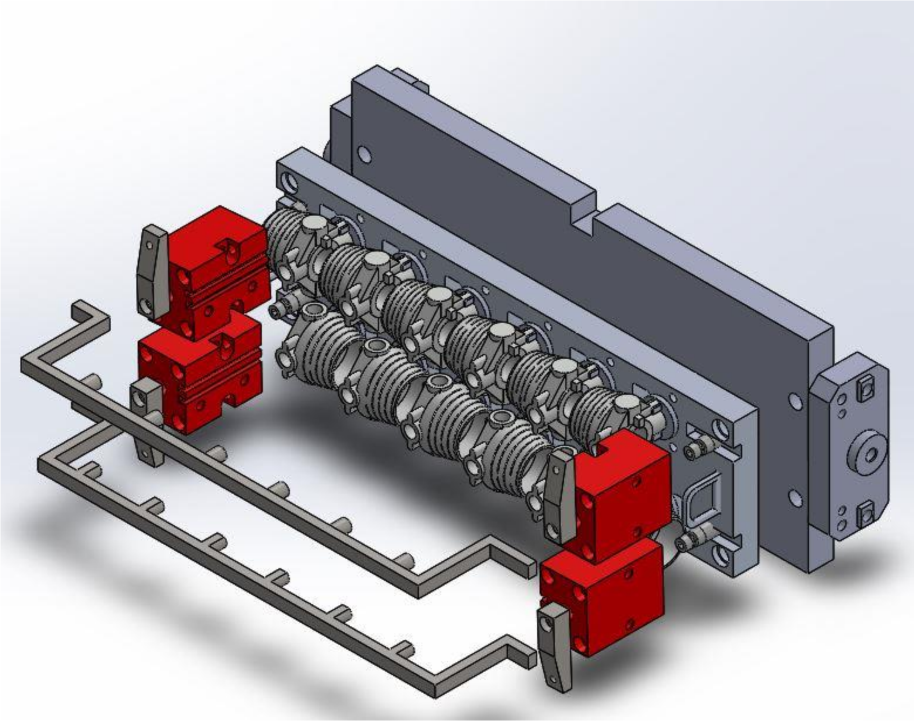


Figure 55 - Design 6-Modular design.

The critical analysis of the modular jig mentioned in Table 20.

Table 20 - SWO Analysis for design 6.

STRENGTH	WEAKNESS
• Its easy tear down modular design. • Low weight and easy ergonomics due to swing clamps. • Could provide the highest process efficiency compared to other design	• It requires more space along the X-axis of the table. • Will be the most expensive of all the previous jig due to the cost and quantity of swing clamps needed. • Require 2 base plate for improved efficiency, almost doubling the initial cost of investment.
OPPORTUNITY	
• Adapt the same design and create a single jig for both fixed and modular design.	

Design 7

In this design, the main idea was to change the clamping style that can open to an angle of 105 degrees. Hence, it doesn't interact in the way of the spindle as shown in Figure 56.

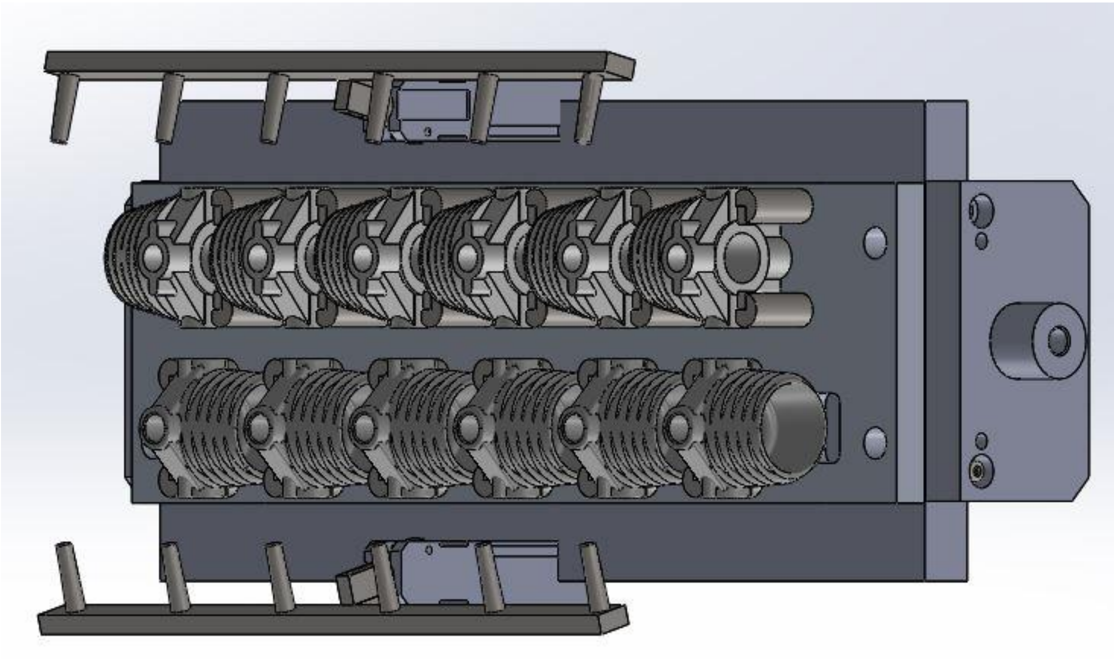


Figure 56 - Design 7-Modular and ergonomic design.

The critical analysis of the jig is discussed in Table 21.

Table 21 - SWO Analysis for design 7.

STRENGTH	WEAKNESS
• It's a dual design with the options of both fixed and modular. • It is less expensive design compared to the previous one due to the reduced quantity of pneumatic actuators. • Redesigned side pins give more grip to the part	• Clamping system not as good as design 6. • Clamping on the top of the plate Is always a liability.
OPPORTUNITY	
• The clamping and ergonomics could be improved.	

3.5 Designing of the main components

This section highlights the important components and their uses, the purpose of the designs and iteration used. Detailed CAD diagrams of all the components mentioned in the section are attached in ANNEX1.

3.5.1 A –Pillar rotatory structure

The A-Pillar is the support structure on which any kind of horizontal surface is rested. Its connected by a shaft on the horizontal surface. It´s an important component of the jig as it helps in rotation around the A-axis. The initial design was inspired from the HAAS half A-Pillar support and dimensioned were changed according to the height of the rotating chuck (160 mm) fixed in the machining table [62]. Which limits the horizontal surface to be not more than 320 mm in height as shown in Figure 57.

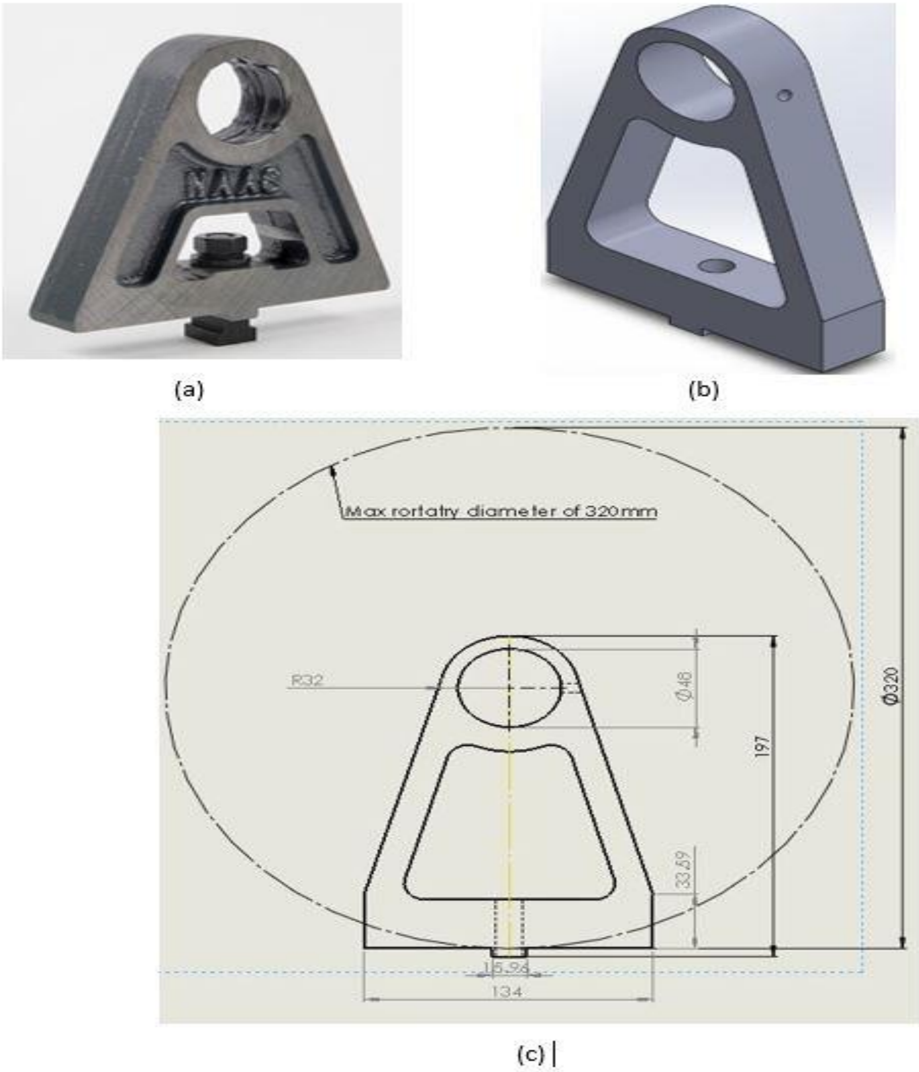


Figure 57 - (a) A support structure from HAAS, Inc [16] (b) 3D CAD model of the A-Pillar (C) Sketch representing the Maximum rotary diameter 320 mm for the designed A-Pilar.

3.5.2 Base Plate

The base plate was designed with the idea on which the machining part Torção 50 was to be mounted. But later iteration of the design changed the functionality of the design making the base plate as the foundation structure on which a modular plate can be screwed or held by clamps to reduce setup times. The iterations of the design change can be seen in Figure 51, 13, 15, 16 and 17.

The deciding aspect of the base plate was the length and shape of the plate. After careful consideration and elimination of non-desirable shapes for manufacturing, the rectangular shaped plate was finalized. The length was predefined one with 540 mm in length and height wise had a maximum of 320 mm. The length of 540 mm was considered, as it was good enough for 6 parts in a row and there was no more usable table space for one more part to be fit in a row configuration. Any extra space of not use is just added weight, so any idea of keeping extra space for future use was neglected. Finally, a rectangular plate with the dimension of 540 mm x 240 mm x 30 mm was agreed to proceed to the next stage of the design.

This component being backbone or skeleton of the jig, it´s required to be extra strong. Hence, a thickness of 30 mm was decided. The sketch and CAD model are shown in Figure 58.

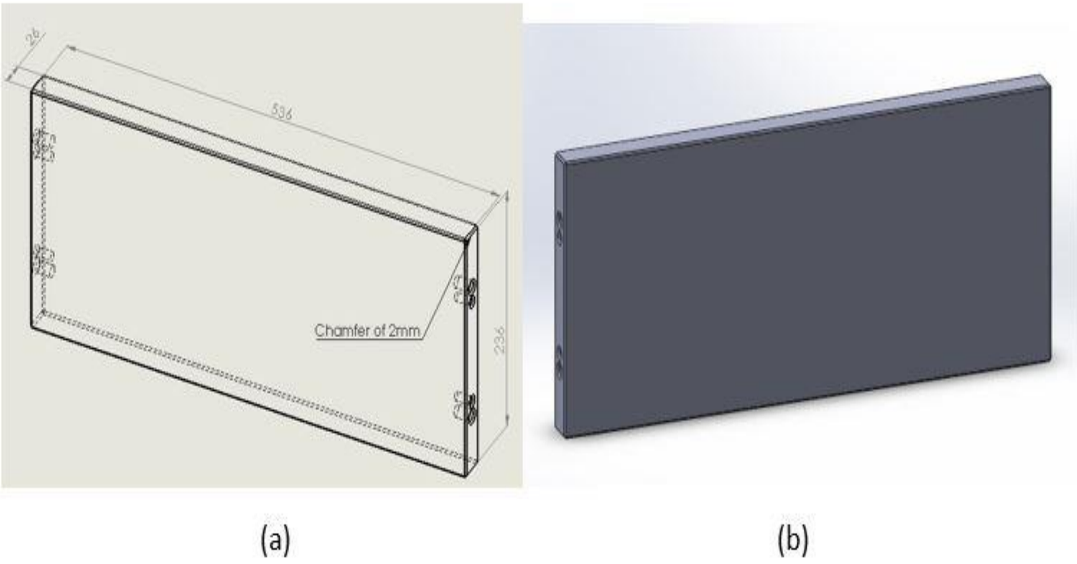


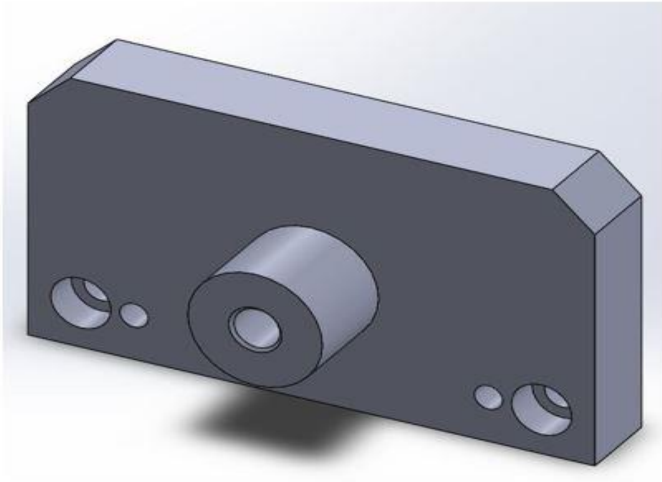
Figure 58 - (a) Sketch of the base plate (b) 3D CAD model of the base plate of dimension 540 mm x 240 mm x 30 mm.

3.5.3 Side Supports

This component helps in attaching the base plate to the rotatory chuck and the A-Pillar. Its another feature is to reduce the thickness of the base plate and providing a strong connection between the A-Pillar, base plate and chuck. Which is crucial for the longevity of the jig. Also, it makes a cheap replacement possible in the future in case of corrosion or breakage of the jig. There is two version of the side support as listed and shown in Figure 59: -

- **A–Pillar Side support** - Requires a long shaft design to accommodate the 30 mm thickness of the A-Pillar. Also, this part requires more height for smooth operation.
- **Chuck Side support** - Requires a small shaft for easy setup and a large hole in the middle for the air tubes for the cylinder.

A crucial aspect of this design is the shaft tolerance and the bronze ring tolerance that provides smooth rotation between A-pillar and A-pillar side support. Another thing to notice is that holes for the screw and pins must align precisely for a flat base plate.



(a)

(b)

Figure 59 - (a) A-Pillar Side support of dimension 160 mm x 91 mm x 55 mm (b) Chuck Side support of dimension 160 mm x 70 mm x 35 mm.

3.5.4 Main Plate

This main plate was designed after concluding a base plate was required as a skeleton for the jig. It was finalised that the part (Winding Cone_1) will be held on to this plate for machining. Its setup was on top of the base plate hence determining the length of the plate was an easy task. But for the height of the plate, it took a lot of trial and error in placing the actual part in a various arrangement using SolidWorks 3D CAD model. It was important to experiment with the height as an important aspect for this plate was to have a good weight to strength ratio. This is primarily due to the idea that the main plate should be built with modularity in mind. But at the same time if it was not a viable option (since it requires at least 2 plates for same use, adding to cost and time) it should be still fixed to the base plate like it´s bonded to it. Some of its design iterations can be seen in Figure 60.

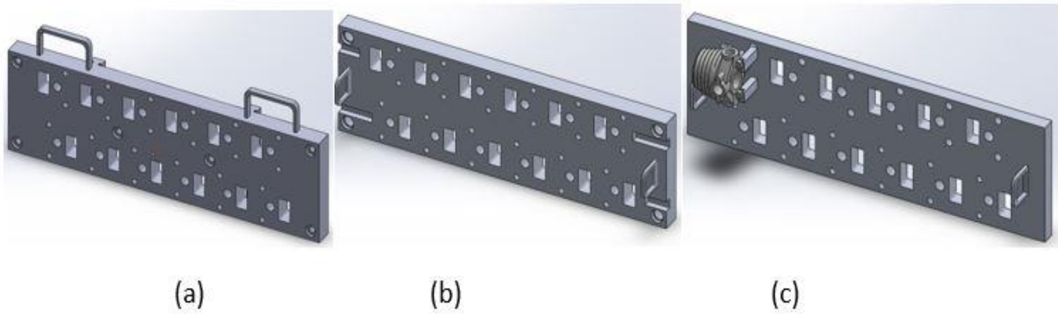


Figure 60 - (a) A sliding over the top main plate for modularity (b) Modular plate used with swing clamp for easy ergonomics (c) lifting parallel to the machining table style modular plate.

The main plate consists of two other subparts to make into the main plate subassembly. Detailed analysis of the pin will be discussed in the coming section. The two types of pins are listed below: -

- **Holding Pin** – It's a conical pin that's the primary holding spot for the part. It's a vital part of the jig as the operator is going to load the part by resting the hole opposite side of the machining side to the conically shaped pin as shown in Figure 61.
- **Supporting Pin** – The tall pin that's shaped to be close contact with runner cut out points as shown in the figure. This pin suspends the rotation of the part around the axis parallel to the main plate.

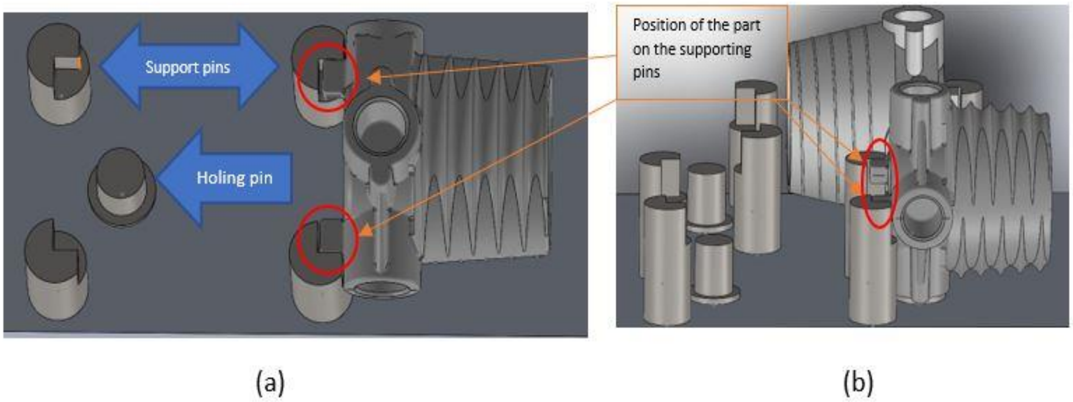


Figure 61 - (a) Top view of the part resting on the holding pin and support pin (b) Front view of the part resting on the pins in 3D CAD assembly.

The design of the main plate was subject to a lot of changes due to the pins shape. The circular design meant that there is always a chance of rotational movement around the pins. The final design with the main plate height of 160 mm was confirmed to be enough for 12 parts to be held and keep the weight of the plate to less than 4 kgs as shown in

Figure 62. Also, the further enhancement was possible in the form of creating `*SHELLS*´ or pockets in an unused area.

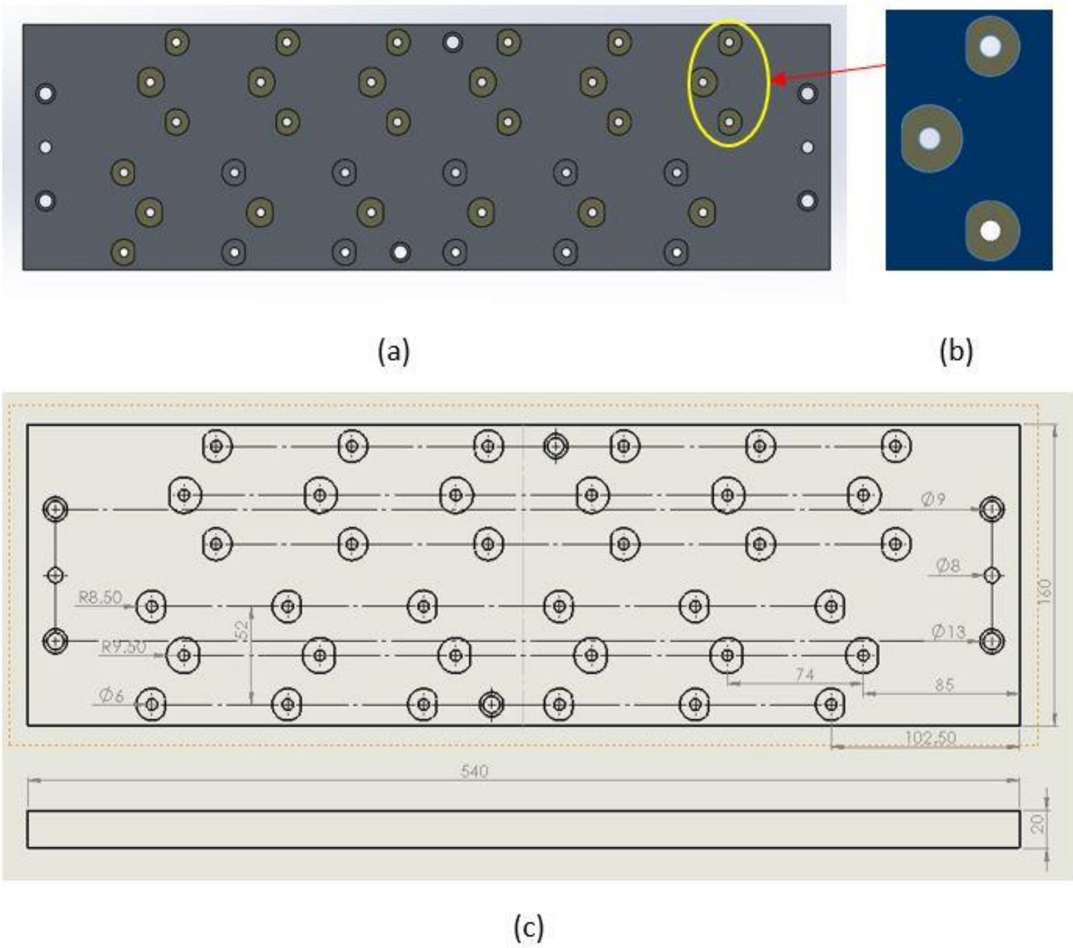


Figure 62 - (a) 3D CAD model of the main plate to be machined (b) Zoomed up an image of pins mounting shape on the main plate (c) Sketch of the main plate with a dimension of 540 mm x 160 mm x 20 mm.

3.5.5 Holding pin and support pin

The holing and supporting pin design started as a single component. But in later discussion and iterations led to designing as a separate component for strength, manufacturability and for easy repairs (maintainability). The pins cuts are required have tight enough spacing to make sure parts don't move. But at the same time free enough to remove and load the parts quickly. One important thing to notice was, there will be some irregularity in the shapes and height of the runner cuts. Figure 63 shows few iterations of the holding pins and supporting pins.

From Figure 63 (g), (h) and (I) it is shown that the final design version of the holding pins and supporting pins. A detailed sketch of the two pins with their dimension is attached in ANNEX1.

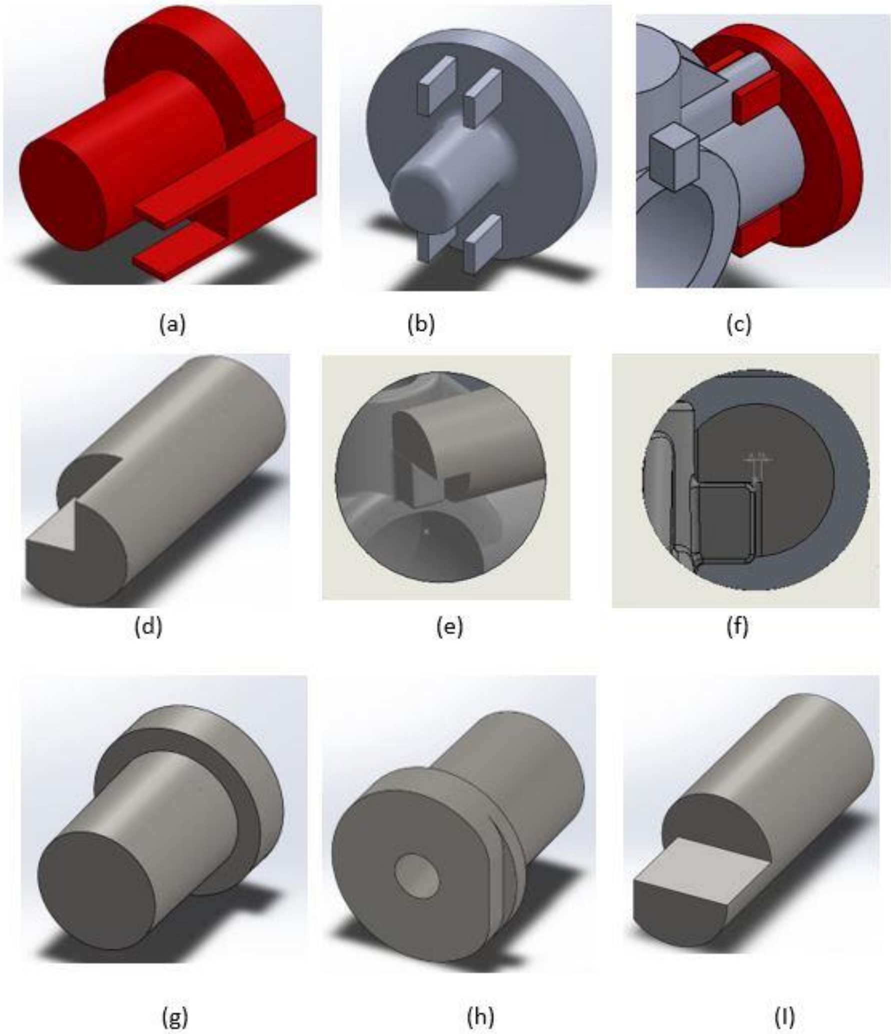


Figure 63 - (a) First design iteration (b) & (c) 2-Holding spot pins (d), (e) & (f) Support pin iteration curving around the runner cut out points (g) Holding pin front view (h) Back view showing the cut out spaces for locking the pins on to the main plate (I) Final design of the support pin.

3.5.6 Clamping Arm

The Clamping arm is an attachment to the pneumatic cylinder that prevents one side of the parts (6 parts on each side) from any further movement after the parts are loaded to the jig. It´s also one component that constantly experiences high amount force from the pneumatic cylinder. The main features that were considered while designing this component are listed below: -

- High strength to weight ratio design.
- A decision on material and thickness after FEA analysis.
- Minimal width design to accommodate the free flow spindle movement.
- Short arm length to minimize the moment caused by the cylinder.

The design was finalised once the type of cylinder and type of mounting was decided. Shown in Figure 64 are few of the clamping arm designs considered.

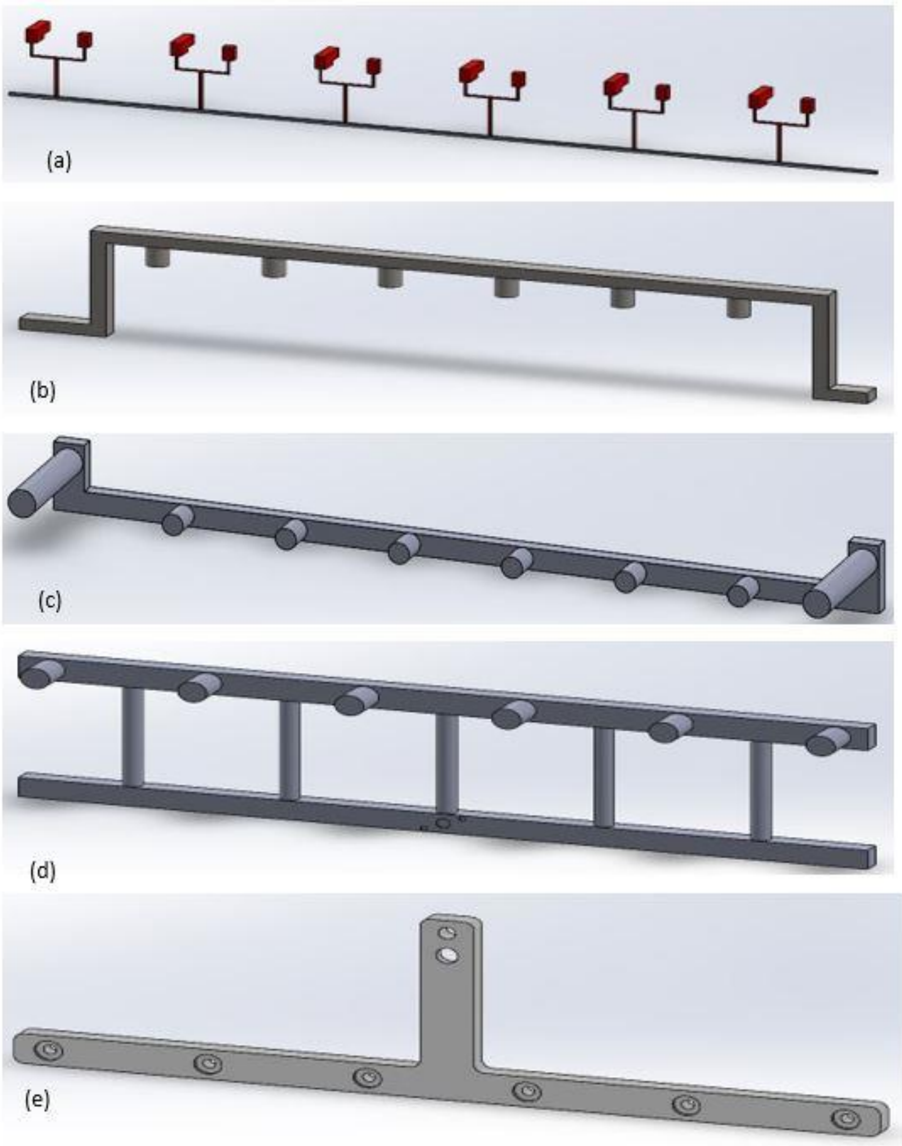


Figure 64 - Iteration of the clamping arm design.

In Figure 64 (e) design was finalised. As stated before the selection of material and thickness of the material contributed to this design. Which is explained later in the chapter about FEA analysis (section 3.9). Also, a detailed sketch with dimensions is added into the ANNEX1.

3.5.7 Clamping Pin

This component is very similar to the holding pin but is attached to the clamping arm and moves along with-it during opening and closing of the cylinder. It´s required for the clamping force needed to keep the part from any kind of movement especially during the drilling process. Figure 65 (d) shows how the pins clamp inside the part from the top.

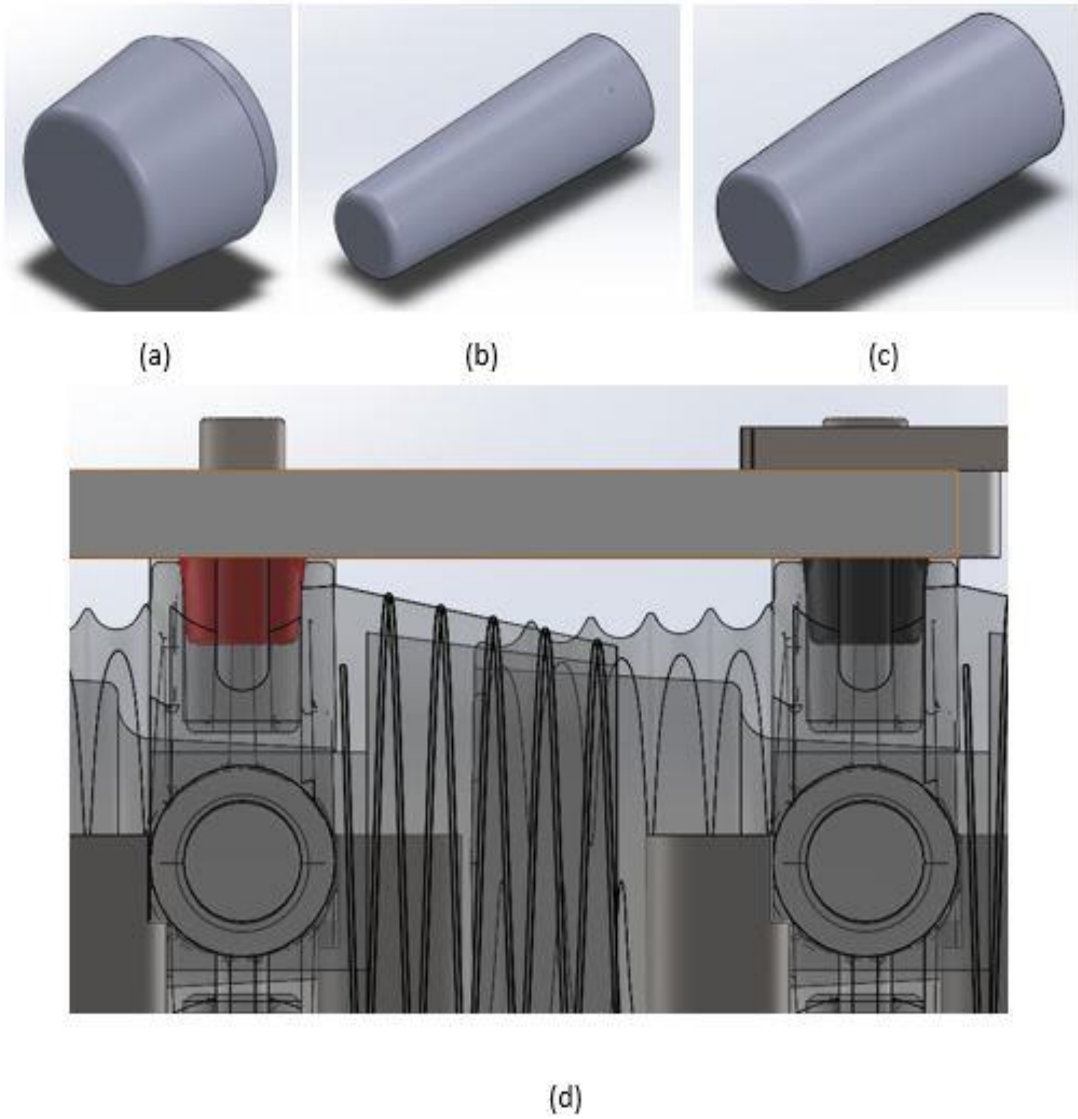


Figure 65 - (a) The final approved design (b) & (c) Other iterations of the design (d) Clamping pin in the closed position of the clamping arm inside the part (transparent mode).

3.5.8 Pneumatic Cylinder holder

The last component is designed to make was an in-house clamp for the pneumatic cylinders. Its function was to hold the pneumatic cylinder in place. The general idea was that from the back of the base plate, there was only 60 mm available for any protruding structure. Also, based on the initial estimation (by using suppliers 3D CAD model) more than 60 mm of cylinder length will be protruding from the back of the base plate. The basic design was inspired by the cylinder front face. In sections to follow there will be more information’s on the cylinder’s specification. The final holder design and sketch are shown in Figure 66.

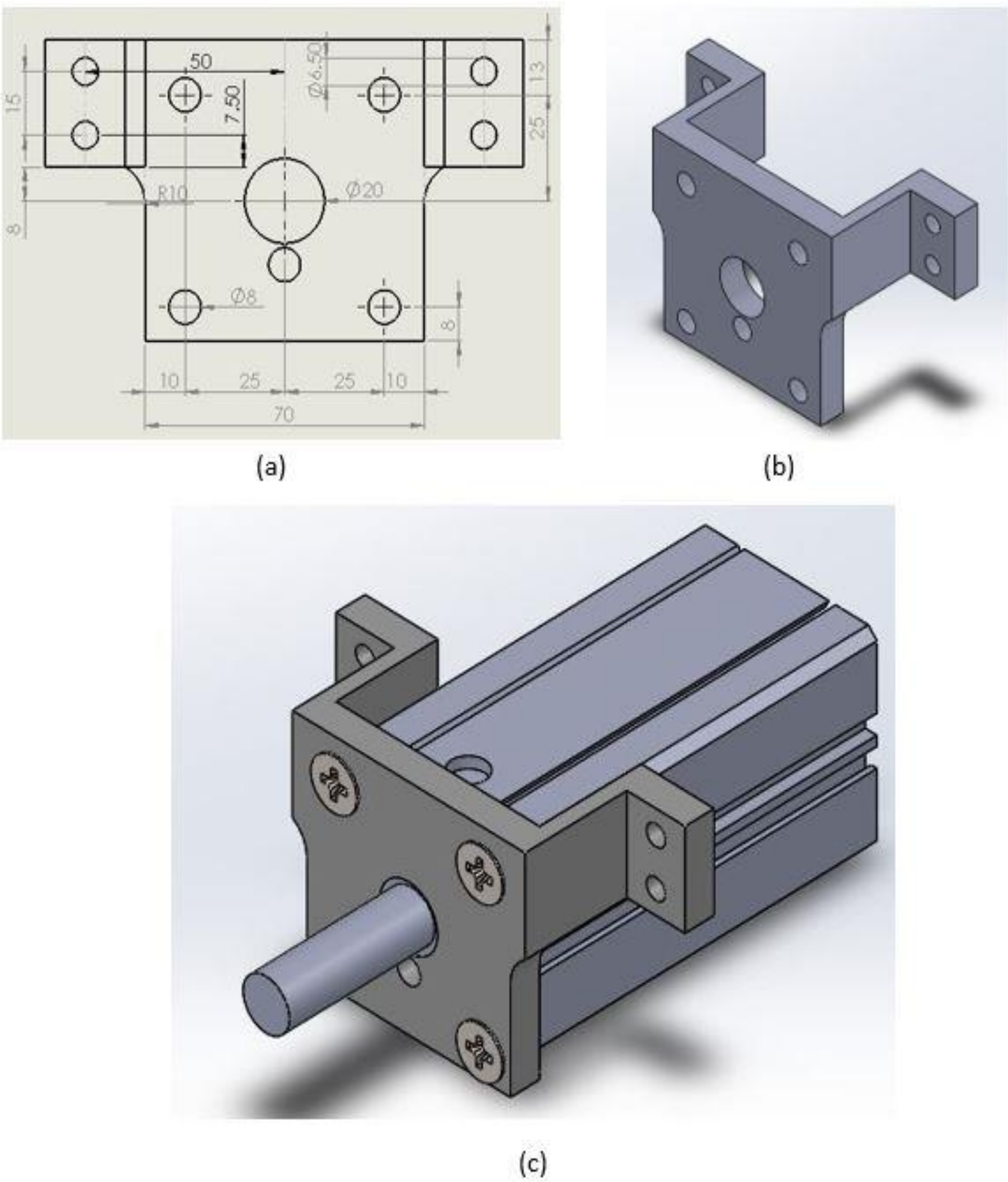


Figure 66 - (a) Sketch of Cylinder Holder (b) 3D CAD model of the Cylinder holder in isometric view (c) Cylinder holder strapped around a pneumatic cylinder (visual representation of its function).

3.6 Feasibility analysis

Katharina Bause et al [63] describe Feasibility analysis as an evaluation of whether an idea can be made realizable under given circumstances. The two main components regarding product development are technical and economic feasibility. But there are other analyses related to starting up of new business and other types of projects, which does not fall under the objective of this report.

3.6.1 Economic Feasibility Studies (EFS)

EFS investigates in the profitability and whether its viable for a company in developing the product. in addition to the objective and the timeframe (established using MS-Project at the start), the most important estimation is effort versus the benefits in the future. The common tool that is applicable in this project is cost-benefit analysis[64].

ASSUMPTION:

- 1 EUR = 1.169 USD [64].
- Making an estimation of the new jigs cycle time based on the current cycle time analysis listed in Table 22 - Assumption on metrics on the new jig Table 22.

Table 22 - Assumption on metrics on the new jig.

METRICS	CURRENT JIG	PROPOSED JIG
Parts per cycle (units)	8	12
Estimated cycle time (seconds)	179.5	240
Total production possible per day (units)	2320	2604
Total number of days required to a machine for the forecasted parts (days)	37.5	33.42
Difference part machined per day (units)	284	
Approximate efficiency possible (%)	12.2	
Savings in number of cycles per day (cycles)	35.5	
Total saving in machining hour for the forecast	59.16	

COSTS:

The overall making of the cost of the new jig is mentioned in Table 23.

Table 23 – An overall estimate of the cost.

CATEGORY	DETAILS	COST (€)
Materials	Based on the weight of the 3D CAD model 200kg of Metallic material €1,71/ Kg [65]	342
Machining	€35/hour of operation cost of CNC (75 hours estimation)	2625
Outsourcing and Accessories	Trying to machine mostly in-house. So fixed cost of €500	500
	Total Cost (approximately)	**3467**

BENEFITS:

Benefits accounts in both economic and knowledge part are the main aspects of this project. The details are listed in Table 24.

Table 24 - Overall benefits in terms of cost.

BENEFITS	COST SAVED (€ PER ANNUM)
12.2% increase in efficiency is 59.16 hour @ €35/hour	2070.6
Knowledge Management	It's a first of its kind project for the company. And for SME, smallest of saving make the biggest difference. Design, CNC codes for manufacturing the jig and a multipurpose jig could shorten lead times of preparing fixtures for future projects
Total benefits (approximately)	**2070.6**

COMPARE:

Total cost / Total benefits possible (years) = **1.67 years or 20 months (Approximately)**

3.6.2 Technical Feasibility Studies (TFS)

The TFS for this project would be about the HAAS VF-2SS machines capability to machine hard steel and its capability machine the parts in the new jig. The specification of the machine is listed in Figure 67 and Table 25.

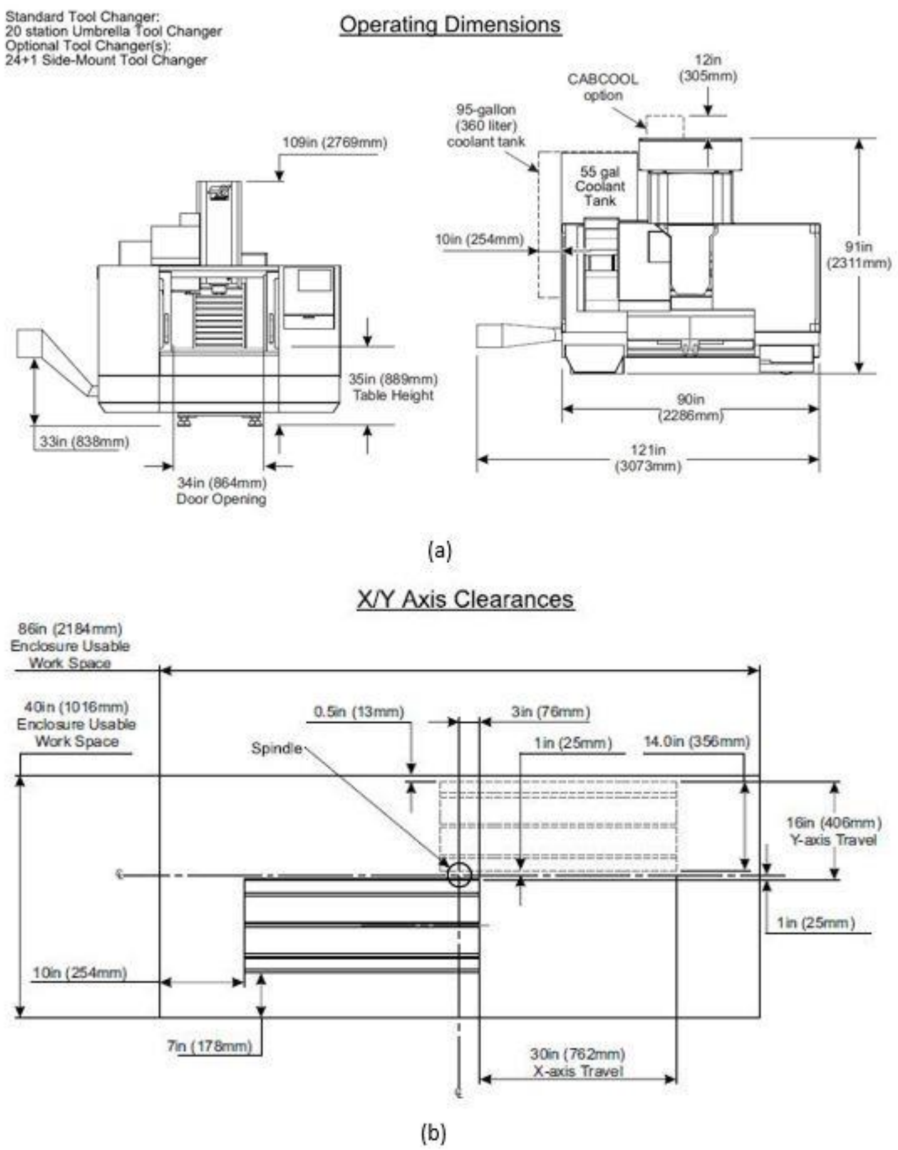


Figure 67 - (a) HAAS VF-2SS machine operation dimension (b) X/Y Axis clearance [66].

List created based on the changeover rules for a design defined by D. Van Goubergen et al [67] are in Table 26. This helps in identifying if the design will meet the requirement.

Table 25 - CNC table dimension [66].

DIMENSIONS	UNITS (mm)
Table Length	914
Table Breadth	368
Spindle Travel Maximum	610

Table 26 - Rules to remember for changeover [67].

RULES TO REMEMBER FOR CHANGEOVER DESIGN	PROPOSED DESIGN
1. LESS WEIGHT	
1.1 Use lighter materials	✓
1.2 Use less material	✓
2. SIMPLIFICATION	
2.1 Reduce the number of mechanisms	✓
2.2 Eliminate the need to remove non-changeover parts	✓
2.3 Eliminate the need to remove complete assemblies	✓
2.4 Eliminate pipe connections or use quick release couplings	✓
2.5 Reduce the number of hand/power tools required	✓
2.6 Reduce the total number of components in a tool	✗
2.7 Simplify control procedures such as timing diagrams	✗
2.8 Use short power drive connections	✗
2.9 Remove complete assemblies/modules that can be prepared off-line instead of removing and mounting several smaller parts in-line	✗
2.10 Use Poka Yoke systems (mistake-proof systems)	✓
3. STANDARDIZATION	
3.1 Use the same size shut heights for presses	✗
3.2 Use the same size securing bolts	✓
3.3 Use the same type of electrical motors	✓
4. SECURING	
4.1 Use the minimum number of fasteners consistent with strength	✓
4.2 Eliminate manually operated clamps	✓
4.3 Use 1/4 turn devices	✓
4.4 Use quick fixtures	✓
4.5 Use hydraulic, pneumatic or electromagnetic fixtures	✓
5. LOCATION AND ADJUSTMENT	
5.1 Eliminate on-machine adjustments	✓
5.2 Provide intelligent adjustment and monitoring	✓
5.3 Eliminate the use of spacers and shims	✓
5.4 Provide dead stop positioning	✓
6. HANDLING	
6.1 Eliminate the need for or ensure easy cleaning/purging	✓
6.2 Eliminate the need to handle hot items	✓
6.3 Eliminate the need to handle awkward items	✓
6.4 Provide power aids	✗
6.5 Provide remote actuation	✓
6.6 Ensure easy delivery of tools etc. to the machine	✗
6.7 Provide good access	✓

3.7 Jig design

In this section various views of the jig, basic dimensions and bill of materials.

3.7.1 General view

The general view of the jig consists various views in-built from SolidWorks and rendered using photoview360 as shown in Table 27 and Table 28.

Table 27 – The rendered images of the new jig.

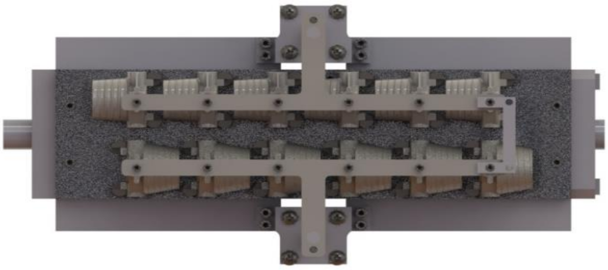
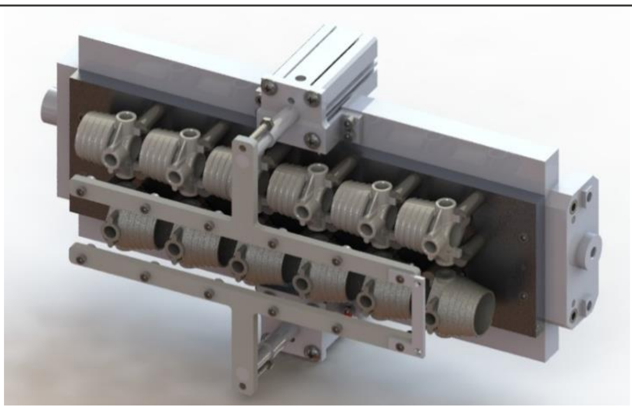
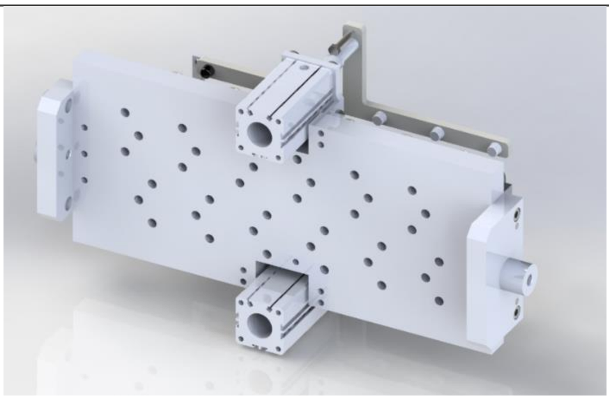
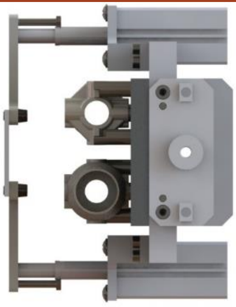
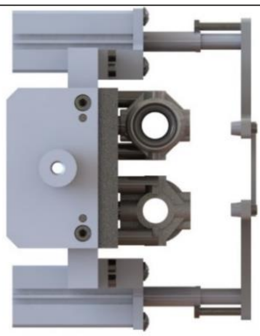
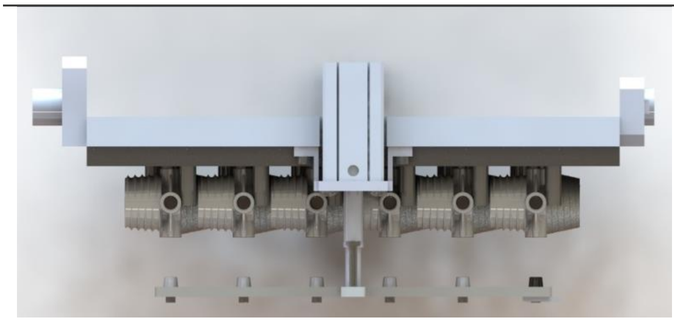
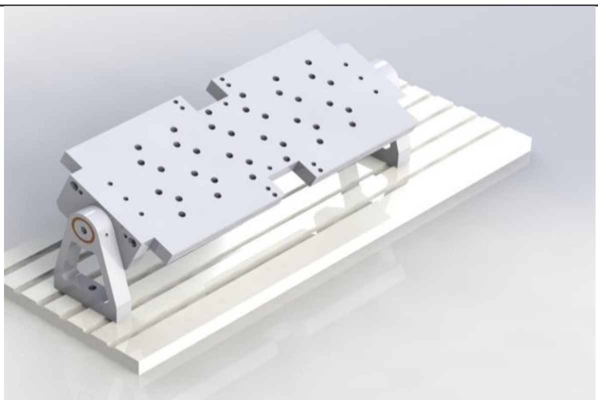
RENDERED IMAGES	DESCRIPTION
	**Front view** – The view that the operator sees while machining.
	**Isometric view** – Shows an overview of the jig**.**
	**Backside view** – The holes at the base plate help in unscrewing and screwing of the support pins and holding without removing the main plate.

Table 28 - Side view images of the new jig

RENDERED IMAGES	DESCRIPTION
	**Right side view** – This is the side that connects with the rotating chuck.
	**Left side view** – This side connect to the A-Pillar with a Bronze ring in between.
	**Top view** – The spindle operating view.
	**Skeleton of the Jig-** This part of the jig will act as the backbone of the current jig and future ones to follow. Hence a tough material is expected to be fabricated.

The SolidWorks diagram in Figure 68 is shown in landscape format for a detailed sketch of the basic outer dimensions of the new jig.

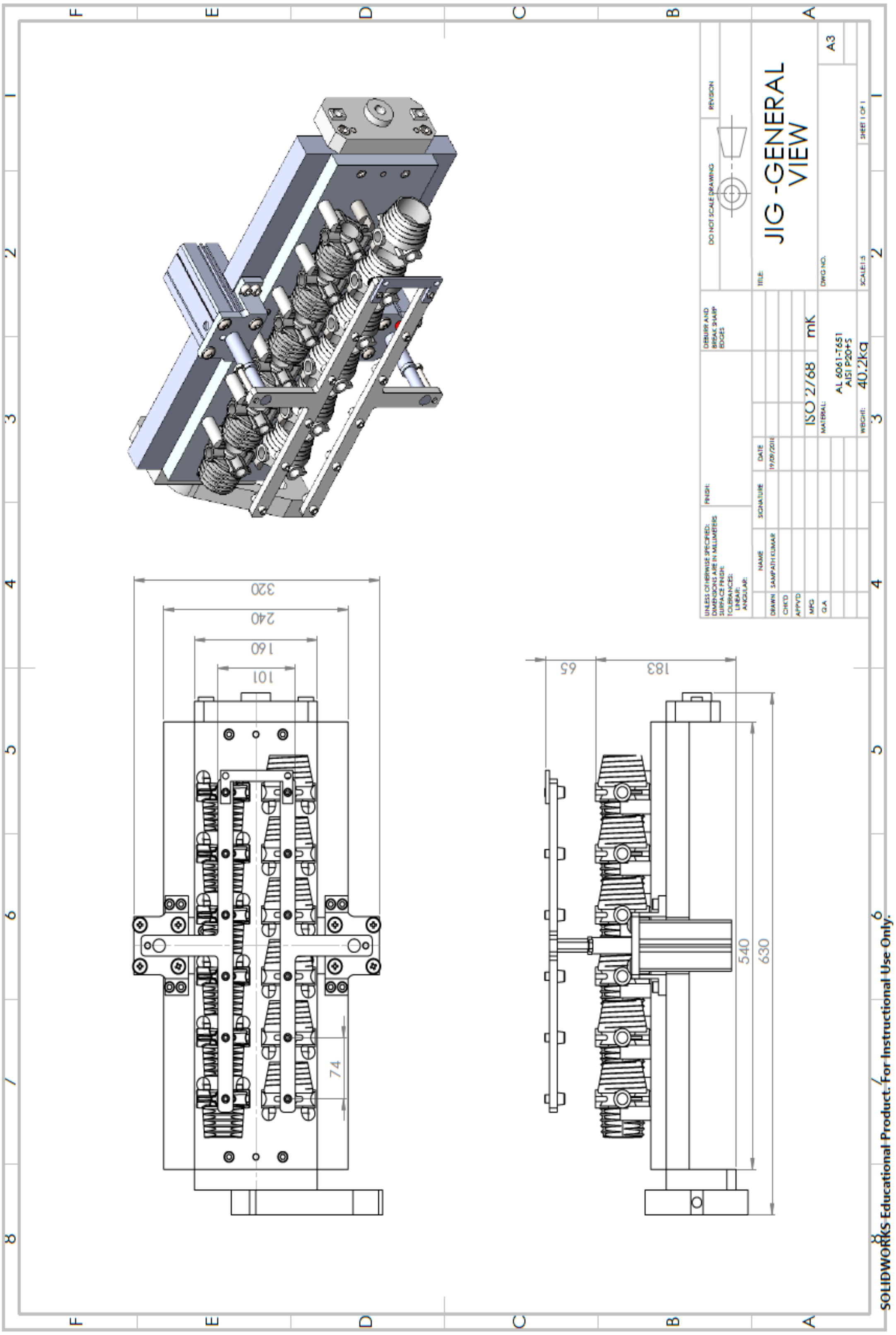


Figure 68 - General views of the jig.

3.7.2 Exploded view

The exploded view is shown in the order the jig would be dismounted. The bill of materials mainly shows the required pins and screws for the jig. Figure 69 is rotated for the better detailing of the exploded view.

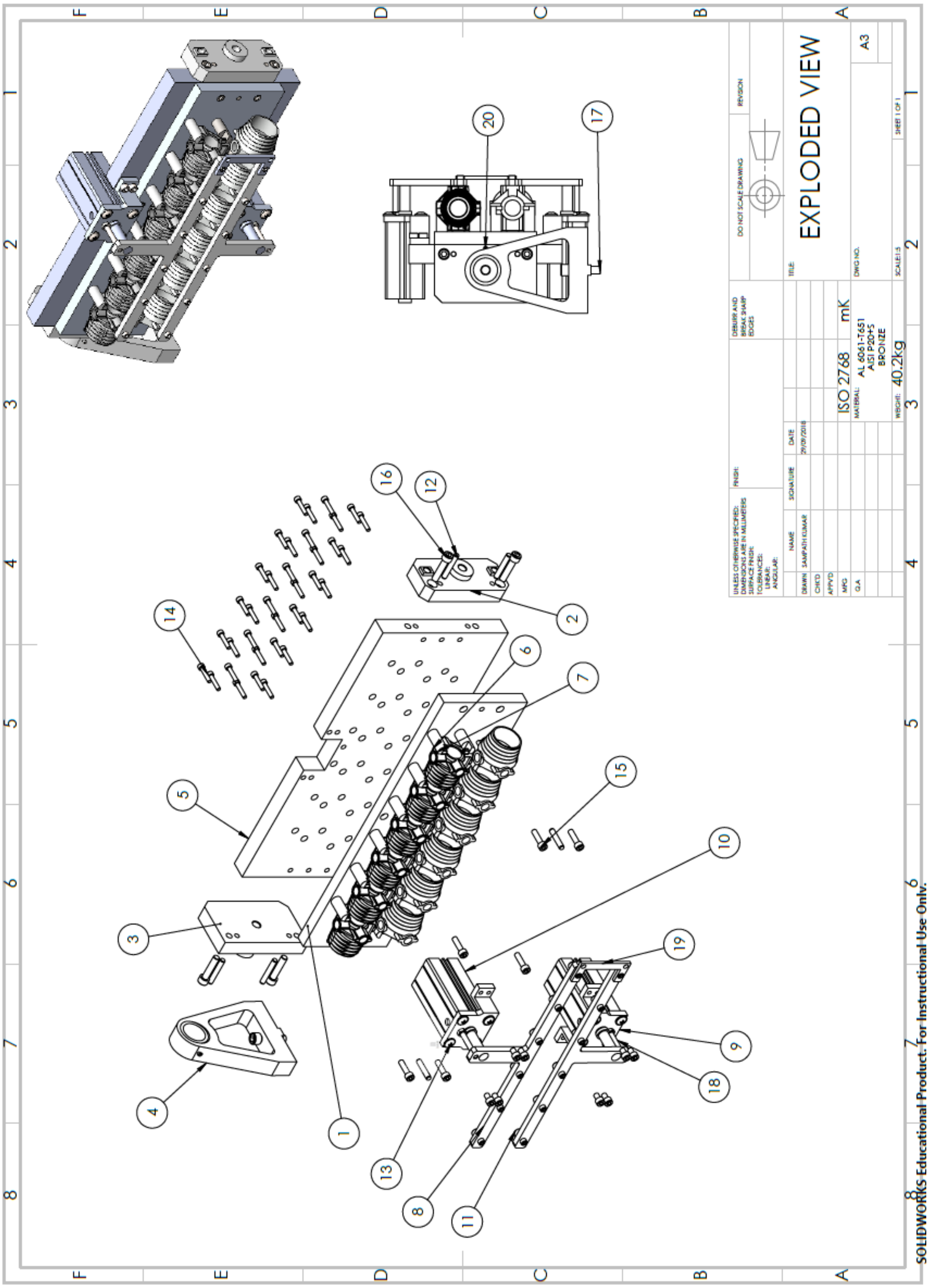


Figure 69 - Exploded view of the new jig.

3.7.3 Bill of materials (BOM)

Listed in Table 29 are the BOM required to assemble the jig.

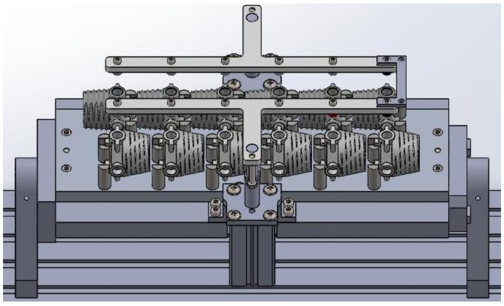
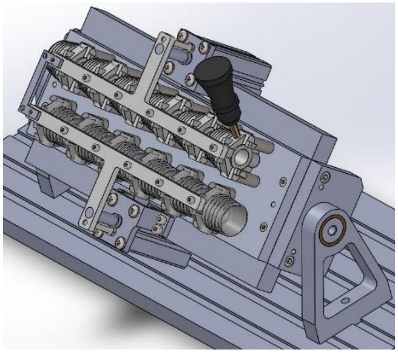
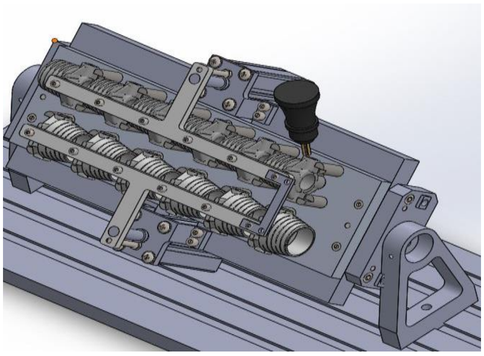
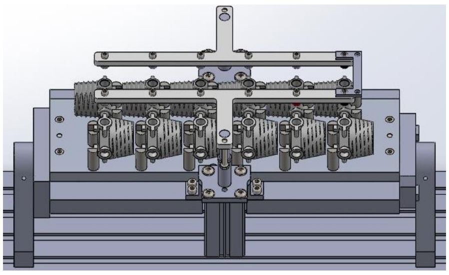
Table 29 - Bill of materials.

ITEM NO.	COMPONENT NAME	QUANTITY
1	Main plate	1
2	Chuck side support	1
3	A-Pillar side support	1
4	A-Pillar rotary structure	1
5	Base plate	1
6	Holding pin	12
7	Support pin	24
8	Clamping arm	2
9	Pneumatic cylinder holder	2
10	Pneumatic cylinder	2
11	Clamping pin	12
12	Dowel pin M8	6
13	DIN 967 -Pan head screw M8	8
14	DIN 912/ ISO 4762 M6	48
15	DIN 912/ ISO 4762 M8	6
16	DIN 912/ ISO 4762 M10	4
17	DIN 912/ ISO 4762 M12	1
18	DIN EN 28765 M8	2
19	U- Bracket	1
20	DIN EN ISO 8747 M6	1

3.7.4 Operation principle

The Jig serves as a customized holding device to machine parts. The jig to machining Winding Cone_1 operates using the program in HAAS controller. The new jig works as the previous jig, in 4-Axis. But the basic shape of the new jig is now rectangular. The coding structure and the overcoming structures that are an abstraction for the spindle are different. Listed below are in points how the jig would work as a visualization based on 3D CAD models.

Table 30 - Operation sequence of the new jig.

DIAGRAM	SEQUENCE OF STEPS
	**1. LOADING** – The pneumatic clamp is raised up using air pressure. The jig would stay flat almost parallel to the machining table.
	**2. FIRST ROTATION** –This is the first machining position. An angle of 45º relative to the machining table. As shown in the diagram the spindle moves through the first row and then will move a short distance in the Y-axis to machine the parts in the second row.
	**3. SECOND ROTATION** - To machine the other side of the Winding cone_1, a second rotation of 90º in counterclockwise from the previous position. But the process is similar for the first process of drilling and the second process of tapping.
	**4. UNLOADING –** The unloading procedure happens in the same position as the loading sequence. And the process repeats itself for the next cycle.

3.7.5 Selecting the standard components

In this section, one will see some of the accessories such as screws, clamps, pneumatic cylinder and support rings. Another important selection procedure is the materials used in building the jig.

3.7.6 Pneumatic cylinder

A critical component in the new jig. The overall design of the jig contributed to selection for the type of actuator to be used and its action. A few of the iteration of actuators that were used in developing the CAD models can be seen in Figure 54, Figure 55Figure 56. The pneumatic cylinders (2 in quantity) used here was custom ordered for a specific amount of stroke and compact length possible. After trial and error for adjusting the cylinder position, a final specification of the cylinder was confirmed as listed below:-

- Diameter - 50 mm
- Stroke - 55 mm
- Overall dimension of the cylinder - 120 mm (L) x 67 mm(B) x 67 mm(W)
- Operating pressure - 800 kPa
- Operating Force - 1571 N (approximately)

Although the Maximum pressure in the HAAS VF-2 SS is 800 kPa pneumatic cylinders generally work at a maximum of 5 kPa that reduce the force to less than 1000 N. The push force is always higher than the pull force. It´s 940 N (approximately) takin in to account the bore size based on the online calculator of forces for pneumatic cylinders [68].

3.7.7 Screws and Pins

The screws and pins were used in DIN EN or ISO standard. The general section of screws and pins was based on the requirement and availability of inventory in the company. There was no need for specific study for the use of appropriate pins. One important use of specific screws required was the one tight the cylinder with its clamp. The purpose was to avoid any obstruction that could be caused if the usual EN ISO 4762 screws were used. The DIN 967 provides a flat head for greater clearance. Table 31 shows various types used and quantity is mentioned in the brackets. Total quantity needed are as follows: -

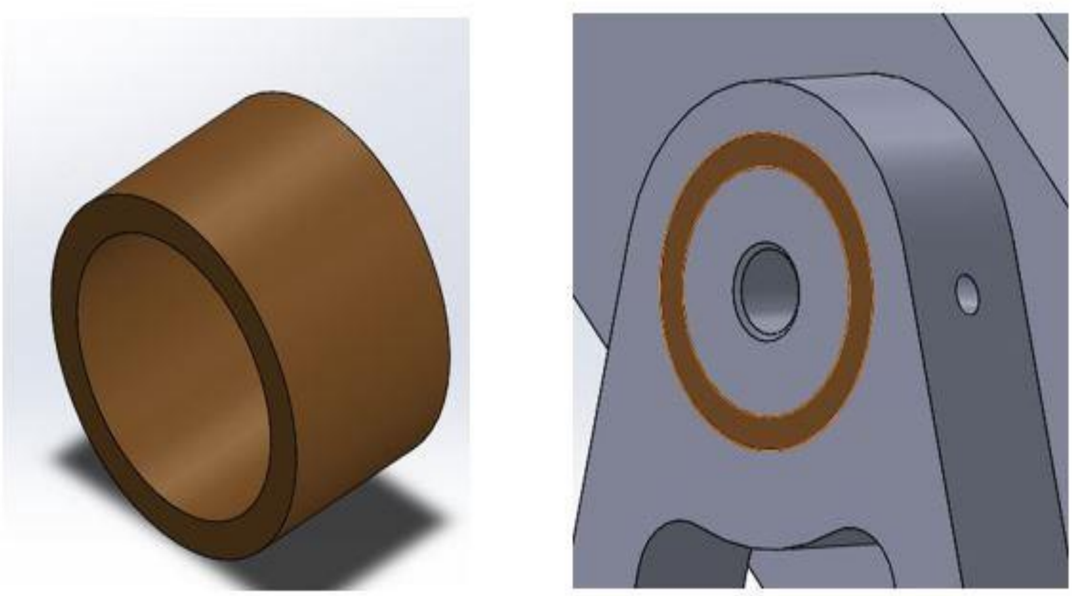
6. DIN 967 – 8 units
7. DIN 912 / ISO 4762 – 70 units
8. DIN EN 28734 – 6 units

Table 31 - Fasteners used in the project[69].

		
DIN 967 - Pan head screw	DIN 912 / ISO 4762 – Socket head screw	DIN EN 28734 – Dowel pins

3.7.8 Bronze ring

Generally, to have a smoother rotation between 2 surfaces of same material a second material is introduced between it. A more malleable material is used for this purpose. In this jig, there is a circular space between the A-Pillar side support and the A-Pillar itself as shown in Figure 70.



(a) (b)

Figure 70 - (a) Bronze ring (b) location of the bronze ring in the A-Pillar.

This part would be outsourced as it requires DIN ISO 268 tolerance of H7 and P6 on the inside and outside of the bronze ring respectively.

3.8 Selection of materials

Material selection itself a is like an event in an organization where many materials are considered from various departments and in each iteration unfit candidates of material are rejected. It’s an important phase of the product development process. Material choices are playing a major role in current design and application of products [70]. General factors that are considered in the material selection process are listed below [71]: -

Performance and function requirement.

Its related to the expected characteristic of the jig. For example, the operation of drilling is going to happen under the use of coolant. Hence, corrosive resistance should be an important attribute of the material used.

Desired physical and mechanical characteristics.

Yield, tensile, creep and fatigue strength are some of the crucial factors as they will help in understanding the stress the jig might experience.

Corrosion and wear resistance.

The service environment understanding is required in designing the jig. Since there are 2 types of main material was needed for the jig. Temperatures that the jig will be working was another factor to be noted.

Easy fabrication.

Fabrication is about how easily welding, or machining could be done for the given material. But also, what implication did these fabrication process have on some important factors. For example, Aluminium is easy on the tools and can be used at higher cutting speed than steel.

Recycling possibilities.

Eco-friendly materials are important and for an organization like Fundwell Lda is of at most priority.

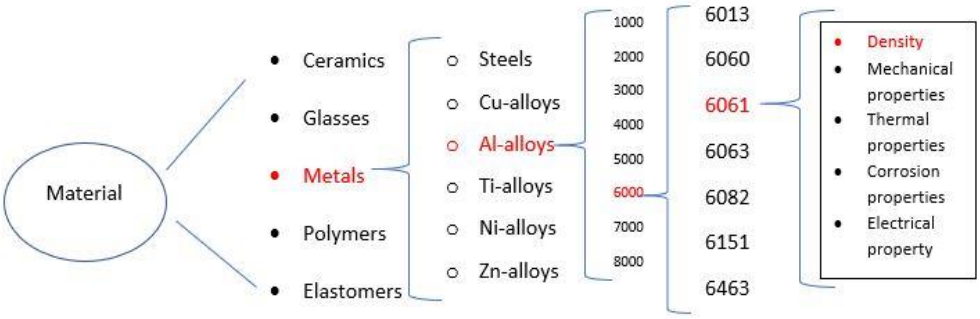


Figure 71 - taxonomy of materials [72].

3.8.1 Selecting the right materials

The starting point was the history of materials that were used in jig making for the company. This was a good starting point. But as soon as the designs started to change, it was realised that skeleton (refer Table 27) needed to be of very strong and long-lasting material and the modular main plate, a lightweight but strong material.

Then with the help of various online tools like ABRAMS Premium steel guide [73] and inputs from the in-charge helped in narrow downing the 2 types of material required for this project. The list is mentioned along with its application below [31]: -

- **Steel 316 (UNS S31600)** – Food processing equipment's, fasteners and springs.
- **AISI P20+S (UNS T51620)** – Jigs, Plastic moulds, die casting moulds and tool holders.
- **Steel 4140 HT (UNS G41400)** - Gears, Jigs and fixture and Piston rod.
- **Aluminium 6061-T651 (UNS A96061)** - Aircraft fittings, camera lens mount and brake piston [31].

The characteristic of the above materials mentioned in the list is listed in Table 32.

Table 32 - Properties of Initial sampled material [74] [75] [76].

MATERIAL	YIELD STRENGTH (MPA)	ELASTIC MODULUS (GPA)	SPECIFIC GRAVITY	MACHINABILITY [A]	CORROSION RESISTANCE [B]	COST CATEGORY [C]
Steel 316	205	193	7.98	3	4	3
AISI P20+S	862	205	7.85	4	5	3
Steel 4140	415	210	7.8	3	4	3
Al 6061-T651	276	68.9	2.7	5	3	4

[A]–> 5 -EXCELLENT, 4-VERY GOOD, 3-GOOD, 2-FAIR, 1- POOR
[B]-> 5 -EXCELLENT, 4-VERY GOOD, 3-GOOD, 2-FAIR, 1- POOR
[C]-> 5 - VERY INEXPENSIVE, 4-INEXPENSIVE, 3- MODERATE, 2- EXPENSIVE, 1- VERY EXPENSIVE

3.8.2 Selection of optimum solution

Now, calculating performance index based on weighing matrix in Table 33. This matrix highlights in the order most important factor to the least among the materials that are initially screened. Since the requirement is for 2 different materials for 2 different purposes. This selection was done differently as the requirements are different.

Weighing Factors

Table 33 - Weighing Matrix.

PROPERTY	SPECIFIC STRENGTH (MPa)	SPECIFIC MODULUS (GPa)	CORROSION RESISTANCE	RELATIVE COST
Weighing Factor	0.30	0.20	0.20	0.30

Calculation of the Performance Index

Table 34 - Ranking with performance index.

MATERIAL	SPECIFIC STRENGTH *0.3 (1)	SPECIFIC MODULUS *0.2 (2)	CORROSION RESISTANCE *0.2 (3)	COST CATEGORY *0.3 (4)	PERFORMANCE INDEX (1)+(2)+(3)+(4)	RANK
Steel 316	7.7	4.8	0.8	0.9	14.2	**IV**
AISI P20+S	32.9	5.2	1.0	0.9	40.1	**I**
Steel 4140	16.0	5.4	0.8	0.9	23.0	**III**
Al 6061-T651	30.7	5.1	0.6	1.2	37.6	**II**

From Table 34, it´s very clear that AISI P20 is the best material to use for this project considering the initial requirements for the jig. Also, needed a second material for the main plate and as expected Aluminium 6061-T651 is the best material to use considering the weight and machinability benefits it offers. This helps in our purpose of making this jig as multi-purpose one. In the next section, using SolidWorks Simulation specific motions of the various component will be studied under force. Also, various materials will also be used to find out the perfect material for the various component.

3.9 Validating the structure using FEM

Finite Element Method (FEM) is increasing its presence as a numerical analysis tool in the field of engineering and manufacturing. The advantage of FEM is applying any material properties to any arbitrary shape in any dimension. Especially for linear problems, it's very easy to obtain accurate and quick results. FEM works based on the concept replacing complex shapes with a summation of very simple shape like triangles, hence the name finite elements [77].

In this project, the one area of concern is the clamping arm. Which is one component under the influence of a force. The solution to be obtained from the FEM stage is to find the appropriate material, thickness and if the length of the arm is strong enough to withstand the force exerted by the cylinder especially during the negative movement (section 2.3.4) Shown in Figure 72 is the detailed view of the **Clamping Arm** component that is subjected to force.

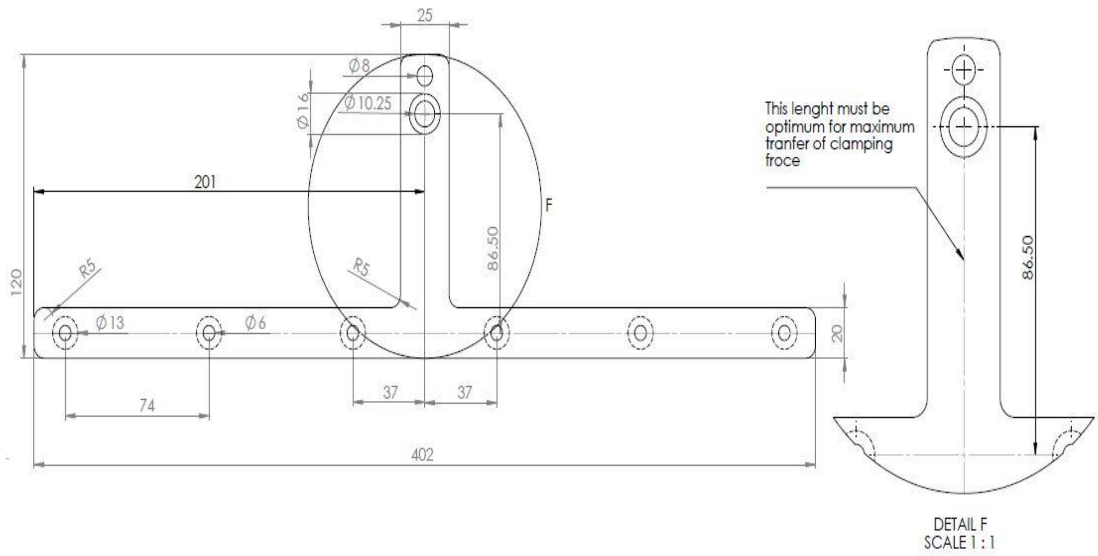


Figure 72 - Detailed view of the clamping arm Length that's under FEA studies.

The methodology for this study is to create a simple static setup demonstrating the arm clamping the Winding Cone_1. To create a simple setup the Winding Cone_1 is replaced by a flat part. This is done to reduce the computational process due to the complex shape of the Winding Cone_1 as shown in Figure 73.

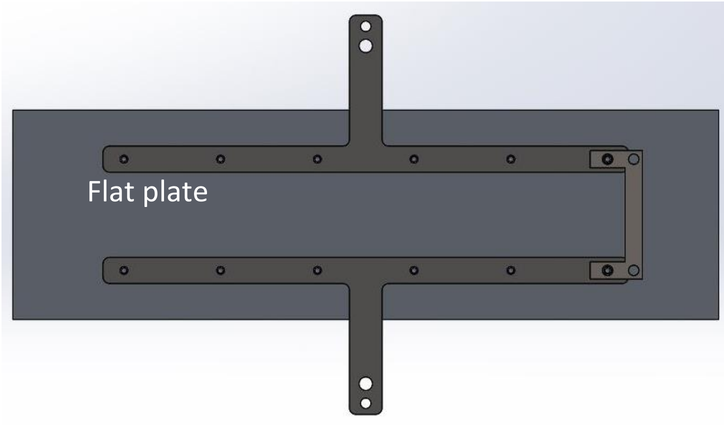


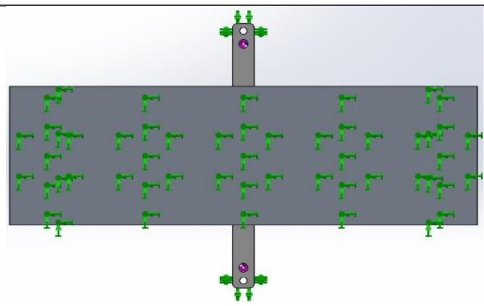
Figure 73 - General setup for FEA studies. Clamping arm in contact to the flat plate.

Also, the solution that’s needed for the project is with Clamping arm dimension and not with the part. Hence, different materials and thickness of the clamp will be modified and analysis which combination gives the best Factor Of Safety (FOS), less displacement and stress in the arm [77].

Parameters

Listed in Table 35 are the various parameter divided into Fixed and changed.

Table 35 - Parameters used in FEA studies.

FIXED PARAMETERS	
Multiplication factor	1
Plate Material	Al 6061-T4 (SS) Equivalent to Winding Cone_1 raw material
Contact set – No penetration	Between Clamping arm and Part (in this case the flat plate)
Contact Set - Bonded	The two-camping arm connected with U-Bracket
Fixtures – Fixed and roller/slides	
Parameters to experiment	
Clamping Arm thickness	5 mm and 10 mm
Clamping arm material	AISI P20 and AL6061-T651
External load	1000 N and 1571 N

Simulation

To start a new static study setup is opened and the four basic parameters needed to be setup: Part material, Fixture, Connection and External load. As mentioned in Table 35 most of this are fixed parameters. The materials of the part will be applied when the part was created. If not, this will be a good moment to apply the desired material.

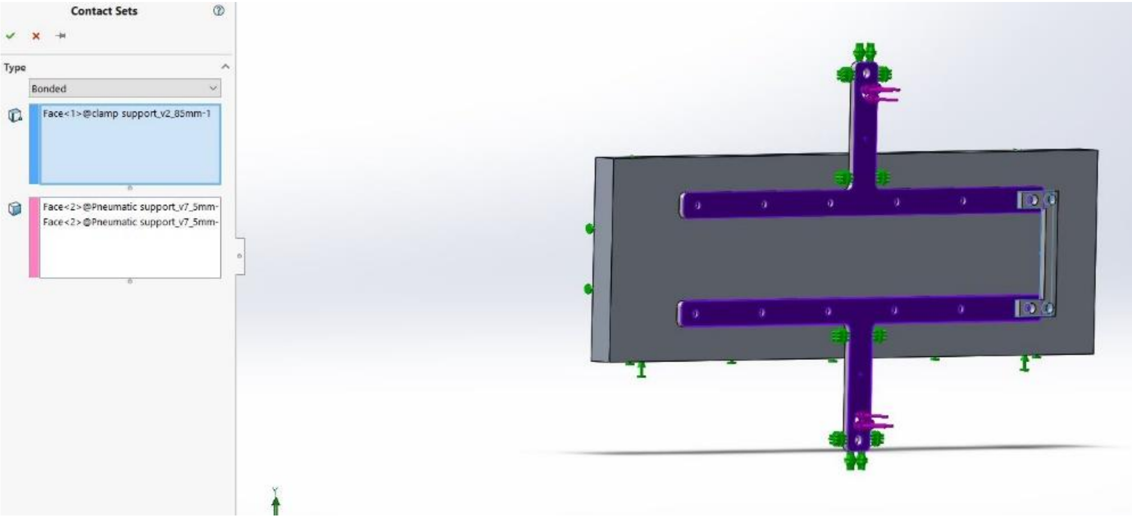


Figure 74 - Setting up connection sets for the clamping arm to be no penetration.

Connections are established by selecting the two surfaces in contact with the desired option as shown in Figure 74. The preferred mesh option is curvature -based meshing as shown in Figure 75. It provides intricate meshing around the complex shapes and coarse around less complicated shapes providing accurate results.

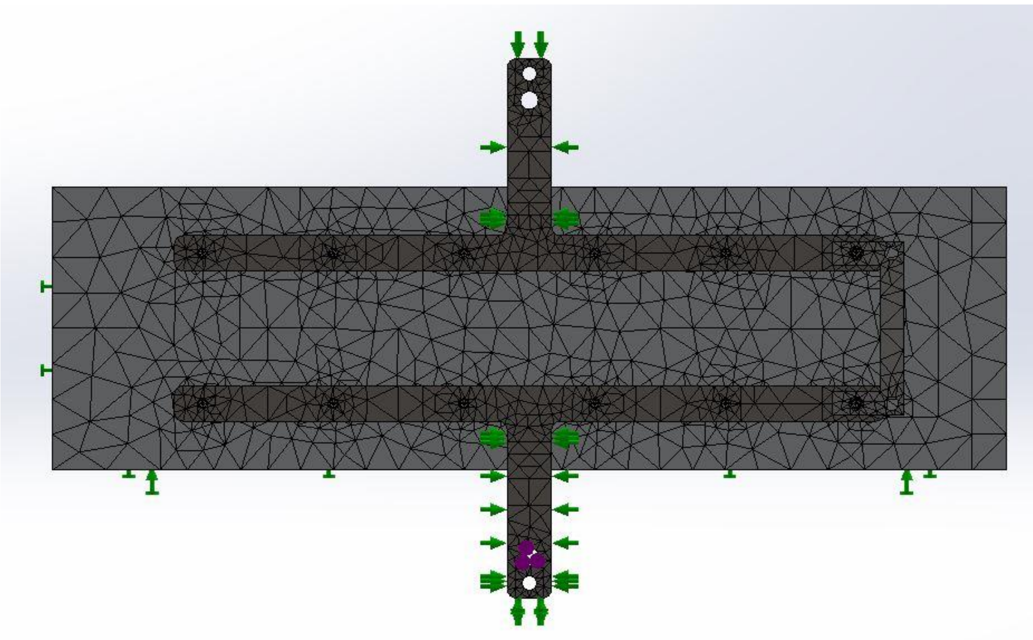


Figure 75 - Curvature mesh-Finer mesh near the pins and screws.

The simulation-1 is run with the parameters mentioned in Table 36.

Table 36 - Variable parameters used in simulation-1.

Parameters to experiment	
Clamping Arm thickness	10 mm
Clamping arm material	AISI P20+S
Primary external load	940 N
Additional secondary external load	1571 N

Results

The stress plot in Figure 76 shows a maximum of 224.5 MPa near the cylinder stroke inlet.

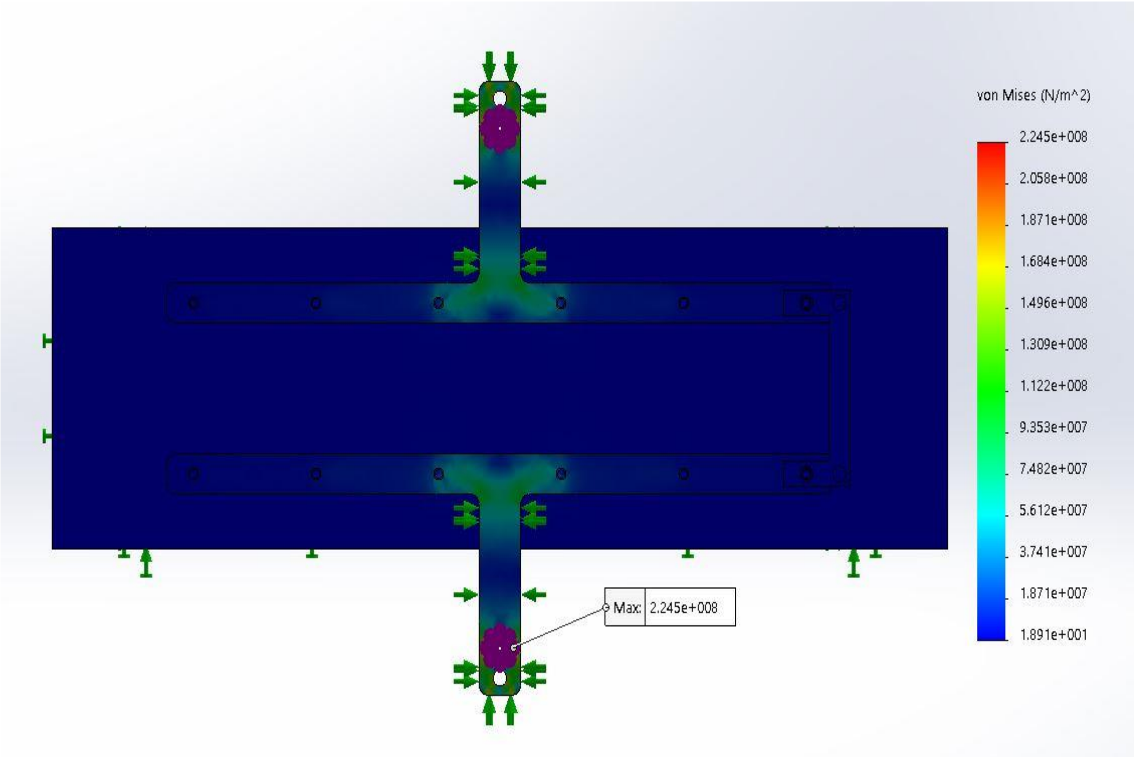


Figure 76 - Stress plot for 10 mm thick clamping arm with a maximum stress of 224.5 MPa.

The stain plot in Figure 77 shows a maximum stain of 6.764e-004 above the cylinder stroke inlet.

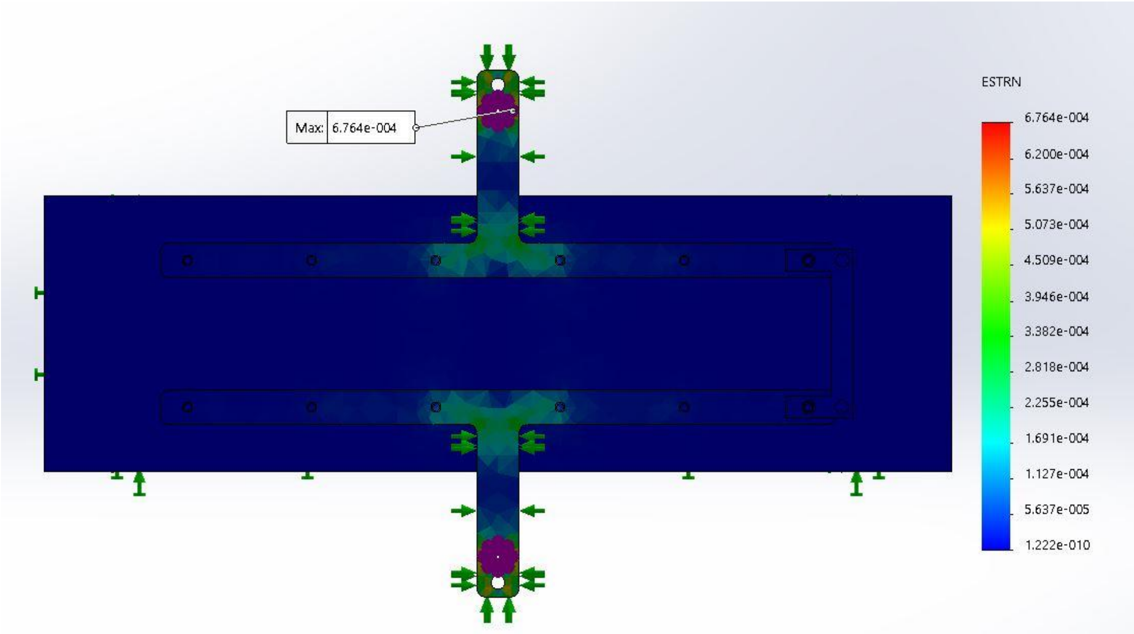


Figure 77 - Strain plot for 10 mm clamping arm with a maximum ESTRN of 6.764e-004.

The displacement plot in Figure 78 shows a maximum displacement of 0.3793 mm at the end of the arm.

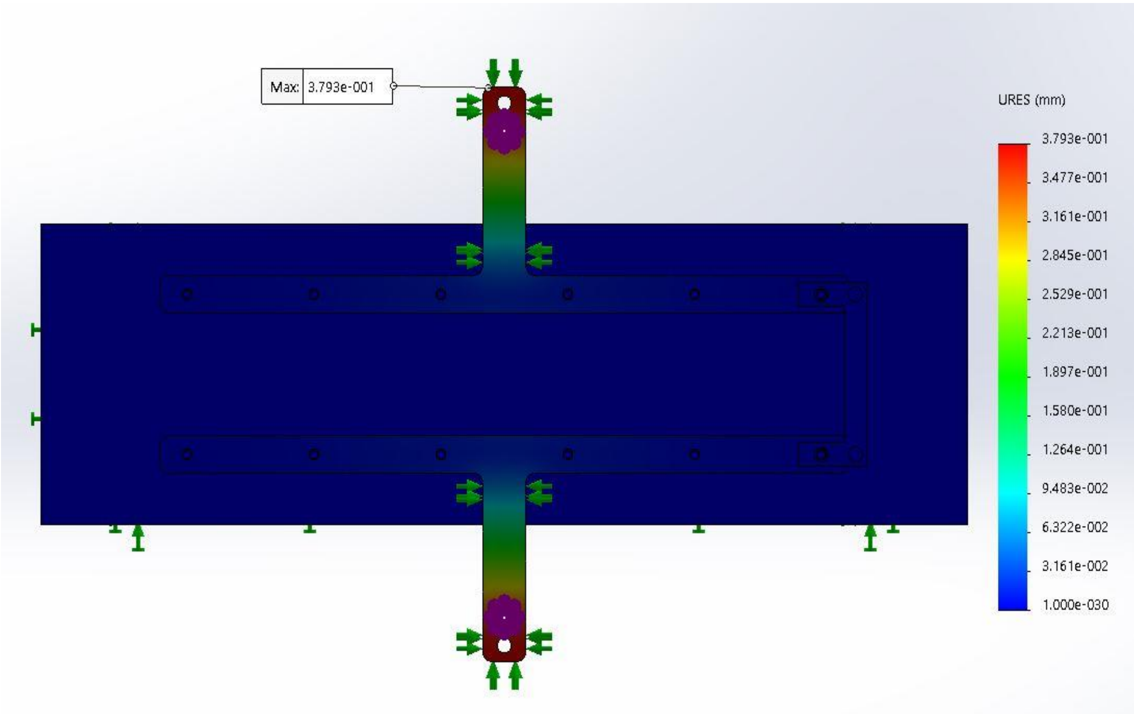


Figure 78 - Displacement plot with a maximum value of 0.3793 mm.

The FOS plot in Figure 79 shows a FOS of 3.7, which qualifies the condition of FOS of more than 1.

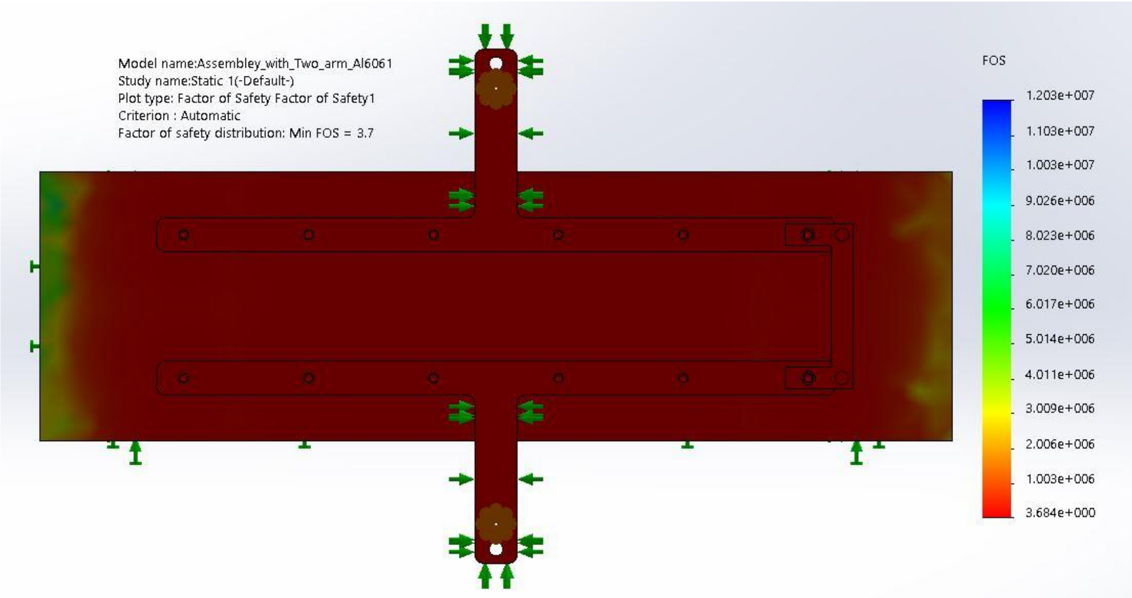


Figure 79 - FOS plot showing a minimum value of 3.7.

Discussion

From Figure 76 and Figure 77 it´s quite clear that the stress and strain region is around the `Y´ region of the clamping arm. The 10 mm thickness of the material P20+S allows for very little displacement and the different colour region on the arm shown in Figure 78 confirms it. Other regions of the arms experience very little displacement.

Figure 79 is the important plot for this design. A minimum value of 3.2 assures that design will not fail when it experiences the pull force. Since this design has and a FOS of more than 1, it can be subjected to much higher force.

Other simulation and results

In the same methodology were used in other simulation and the results are plotted in a graph due to the space constraint in the report. Detailed images of the other simulation are attached to the ANNEX3. Various details of simulation parameters are listed in Table 37.

From the simulation results in Table 37, one can conclude that the 5mm thickness for the clamping arm is not a feasible design based on simulation 1. The simulation 3 which uses aluminium is also not possible as minimum FOS is just 1. Even if it passes the criterium 1 < FOS < 8. So, only simulation 2 has an acceptable displacement in the arm and a FOS of 3.7 at the normal operating condition. And simulation 4 justifies that even at peak operating conditions the selection of the material P20+S at 10 mm thickness is the best optimal solution available with a FOS of 2.2. The comparative chart of all the simulation is shown in Figure 80.

Table 37 - Simulation variables and results.

SIMULATION VARIABLES FOR EACH SEQUENCE			
Sequence	Arm thickness (mm)	Material	Force (N)
Simulation 1	5	P20+S	940
Simulation 2	10	P20+S	940
Simulation 3	10	Al 6061-T651	940
Simulation 4	10	P20+S	1571
SIMULATION RESULTS			
Sequence	**Stress *e+002 (MPa)**	**FOS (no units)**	**Displacement (mm)**
Simulation 1	1.324	0.62	6.002
Simulation 2	2.245	3.7	0.3793
Simulation 3	2.189	1	1.103
Simulation 4	3.752	2.2	0.633

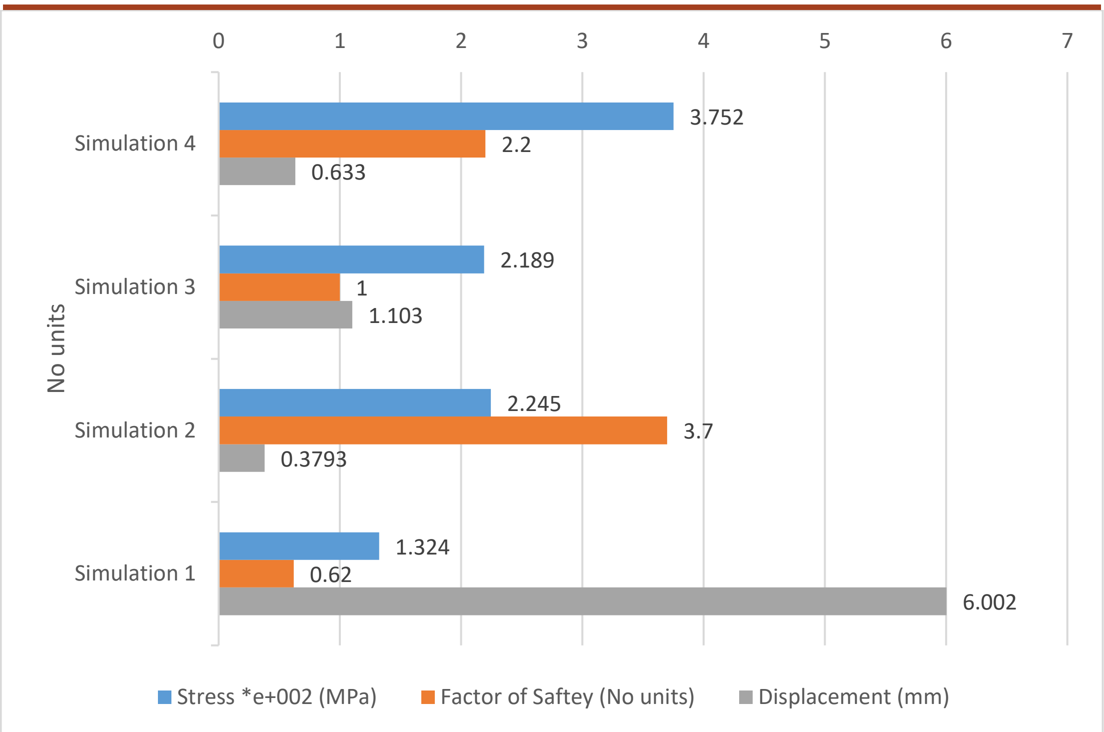
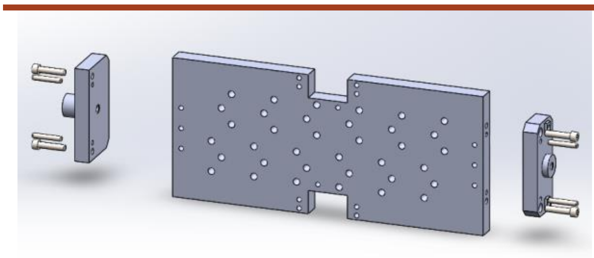
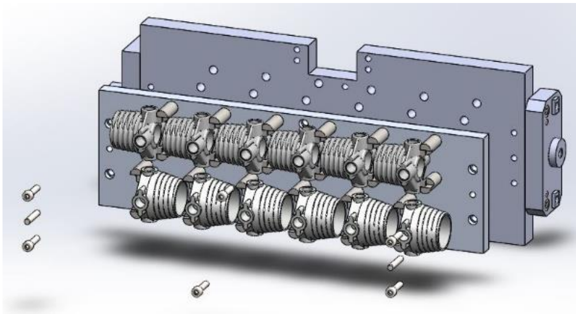
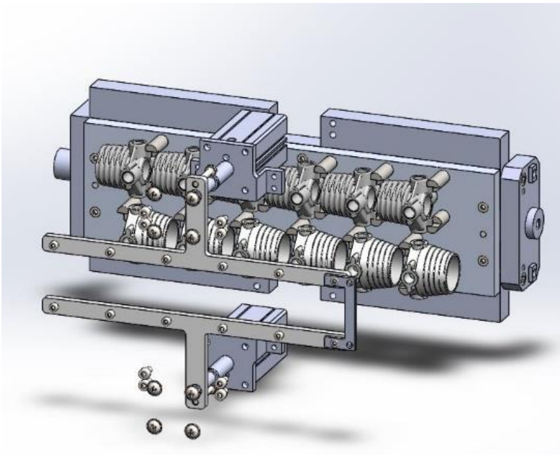
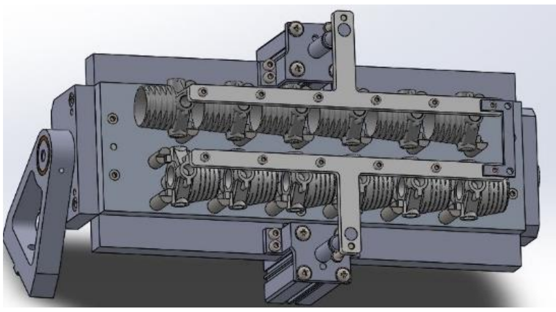


Figure 80 - Simulation results plotted for stress, FOS and displacement.

3.9.1 Assembly manual

The Assembly process consists of simple procedures that are listed in Table 38.

Table 38 - Assembly Guide.

	**Step 1**- Firstly, assemble the Chuck side support and A-pillar side support to the base plate with 2 Dowel pins and 4 M10 screws. This is called the Skelton of the jig
	**Step 2** – Secondly, Attach the main plate with the Skeleton using 6 M8 screws and 2 dowel pins and tight using Hex keys. The holding pins and support pins of the main plate subassembly is a straightforward assembly with contours that acts like the Poke-Yoke system and fastened by 36 M6 screws.
	**Step 3** – The next subassembly to be connected to the base plate is the cylinders with the clamping are using 8 of pan head and screw head each in M8 configuration. The cylinder with clamping arm is kept as a subassembly instead of an individual part because of the small clamping pins and its screw are easy to lose track of and saves a lot of time in keeping it as a subassembly.
	**Step 4** - The final component to assemble is the A-Pillar its corresponding support. And it’s ready to be setup in the table. There is a bronze ring in between the A-Pillar and support shaft. It´s pre-assembled with the A-Pillar with a tightening pin.

3.9.2 Budgeting

The cost for this jig consists of materials used, machining expense, Stipend of the intern and accessories for the jig. It's an important aspect of this project because for a bring profit by increasing the overall efficiency of the process. But if too much is spent on the initial part of making the jig, it would take a longer period to break even and reap profits of the new jig.

The cost was tracked along the full course of this project in regard to machining time and the type of components and materials to be used for fabricating the jig. An explanation about the jig fabrication is detailed in section to follow. Table 39 shows the total amount spend on the jig.

Table 39 - Overall costs of the jig making process.

DESCRIPTION	UNITS	TOTAL COST (€)
Material		
Aluminium	1	110.7
Steel 1.2312 (P20+S)	6	553.5
Machining		
Total machining time at €35/hour	43.58 hours	1525.4
Outsourced Parts cost		
Base plate		
Holding pin and Support pins	36	360
Clamping pins	12	100.8
Bronze ring	1	20
U-Bracket	1	10
Fasteners	70	14
Pneumatic cylinder	2	138.76
New Tool holder and tools	2	214
Final Total Cost		**3047.16 (approx.)**

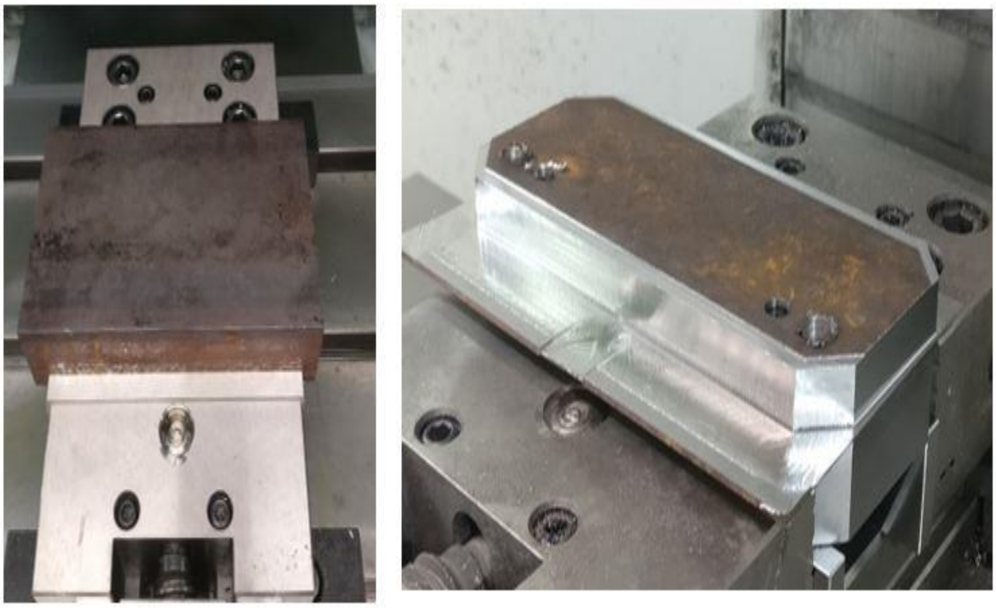
3.10 Jig fabrication

The important aspect of this jig making from the company´s perspective was more than just improving the process. It was also about making components in-house. It was the challenging part of this project as the resources to machine the jig were few. Like, the luxury of using CAM software's was not available. Machining was primarily done through the help of sketch and diagram from SolidWorks.

Also, the HAAS VF–2SS didn't have the ideal setup for machining heavy block of steel. But in the manufacturing process overcame these issues using various solution which will be shown in sections to follow.

3.10.1 Chuck side support

The fabrication of the chuck side support started as a block of steel with dimension 180 mm (L) x 80 mm (B) x 40 mm (H). The machining of the component was divided into various stages and a CNC program was developed. Figure 81 shows how the exterior contour of the chuck side support looked after using a simple subprogram.



(a) (b)

Figure 81 - (a) A block of steel attached to a milling vice (b) Exterior shape been profile milled by CNC subprogram.

The CNC sub-program used in the HAAS controller is mentioned in Table 40 to understand how these codes are used to mill the desired shape. For a better understanding of the G-code function, its encouraged to refer ANNEX2 for the full list of codes and its description are mentioned.

Table 40 - G-Code for the exterior contour of chuck side support.

G-CODE FOR EXTERIOR CONTOUR	DESCRIPTION
N10 G01 G91 Z-0.5 F500	• Sub Program number `N10´. • G91 (incremental coordinate system) drops the spindle in 0.5mm in negative Y-axis from its previous dimension. • F500 – Feed rate of 500mm per minutes.
G01 G41 G90 D01 Y42.5 F500;	• G01 is for Linear interpolation (refer literature review). • G41 Left side cutter compensation for the tool `D01´ with the diameter of the tool predefined. • Y42.5 is the first cutting point of the tool on the block, in this case right at the middle with a feed rate of 500mm per minute. Also, G90 defines absolute coordinate and instructs the tool to move to 42.mm in positive direction irrespective of the previous position.
G01 X-590,C12 F800:	• From the point Y42.5 the tool moves in X-axis to the make a chamfer for 12mm as defined by the command `C12´. It moves till 590 in the negative X-axis. • The tool cuts at a feed rate of 800mm per minute.
G01 Y112.5,C12;	• From the Previous point of X-590 moves in positive Y-axis till Y112.5 with a chamfer of 12mm at the same feed rate.
G01 X-430,C12;	• From the Previous point of Y112.5 moves in positive X-axis till X-430 with a chamfer of 12mm.
GO1 Y42.5,C12;	• From the Previous point of X-430 moves in positive Y-axis till Y42.5 with a chamfer of 12mm.
G01 X-510;	• Return back to the first cutting point in the X-axis at the same feed rate.
G01 G40 Y15 F1500:	• G40 implying that no cutter compensation. • Tool moving to the safe position of Y15. Which is essential to do loops and mill in layers.
M99;	• Sub-Program ends for the exterior contour and control goes to the main program. And if there is a loop, the sub-program will repeat again.

Similar to Table 40, there are various sub-programs that are needed to machine the desired component as shown in Figure 82. But due to the space constraint and given that the project highlights the improvement of the process. The need for detailed manufacturing process explanation is not required. As a fully outsourced Jig would serve the objective too.

Figure 82 - Machined chuck side support.

But as mentioned in the general requirement and one of the objectives of the project. The entire process serves as part of knowledge management. A tacit knowledge (referring to design language) can be preserved using diagrams, 3D CAD models, G-codes and reports. In a later section, the benefits of creating a jig like this in-house will be justified. Listed in Table 41 are the operations carried on shaping up the required component with machining times of each operation. It's important for the better accurate calculation of the overall budget of the jig.

Table 41 - Operations and used in machining of the chuck side support.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (min)
1	Face Milling	20	70
2	Profile Milling	20	200
3	End Milling	20	50
4	Drilling	8, 10.25, 11, 13 and 17	30
	Total time		**350**

Similarly, the different type of tools used in the machining processes is listed in Table 42.

Table 42 - Tools used in the machining process of the jig components.

TOOL IMAGE	TOOL TYPE	TOOL DIAMETER (mm)
	3 Flute Endmill with the interchangeable cutter	20
	For drilling operation and chamfer.	17, 13 and 11.5
	For drilling operation and chamfer.	6, 6.5, 8, 9 and 10.25
	For contouring, boring and pocketing.	8 and 6
	Point tool for marking	1
	For pocking in the main plate	6

3.10.2 Chuck side support

The A-Pillar side support follows the similar procedure of the chuck side support. It´s made from a block of steel of dimension 168 mm (L) x 100 mm (B) x 60 mm (H). The subprograms used for the previous component was also used in this support structure with dimensional changes. Examples are the profiling and facing operations. Figure 83 shows how the component was machined.

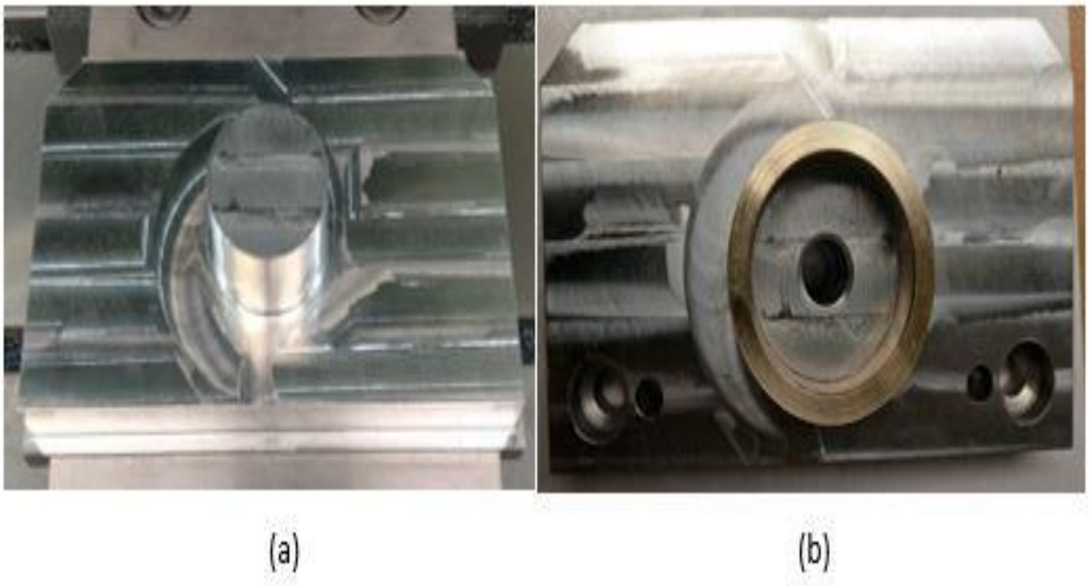


Figure 83 - A block of steel after pocketing and profiling (b) Machined part with a bronze ring attached to check fit.

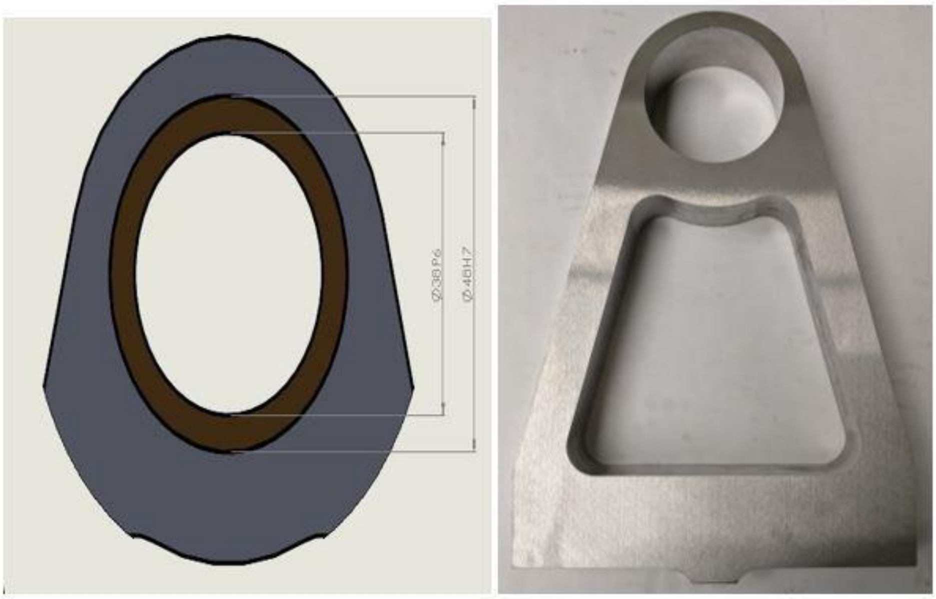
The list of operation carried on and their timing is listed in Table 43.

Table 43 - Operations and timing in machining of the A-Pillar side support.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (min)
1	Face Milling	20	90
2	Profile Milling	20	180
3	End Milling	20	56
4	Drilling	8, 10.25, 13 and 17	30
	Total time		**356**

3.10.3 A-Pillar rotary support

The rotary support requires precise machining due to the tolerance rating for the bronze ring. The hole diameter of 38 mm required H7 (Sliding fit) and the other diameter of 48 mm of the bronze ring required P6 (Locational transition fit) as shown in. The machining process started with a similar block of steel like the previous component of size 200 mm (L) x 140 mm (B) x 35 mm (H).



(a) (b)

Figure 84 - (a) Detailed view of the tolerance requirement (b) Polished and fully machined A-Pillar support.

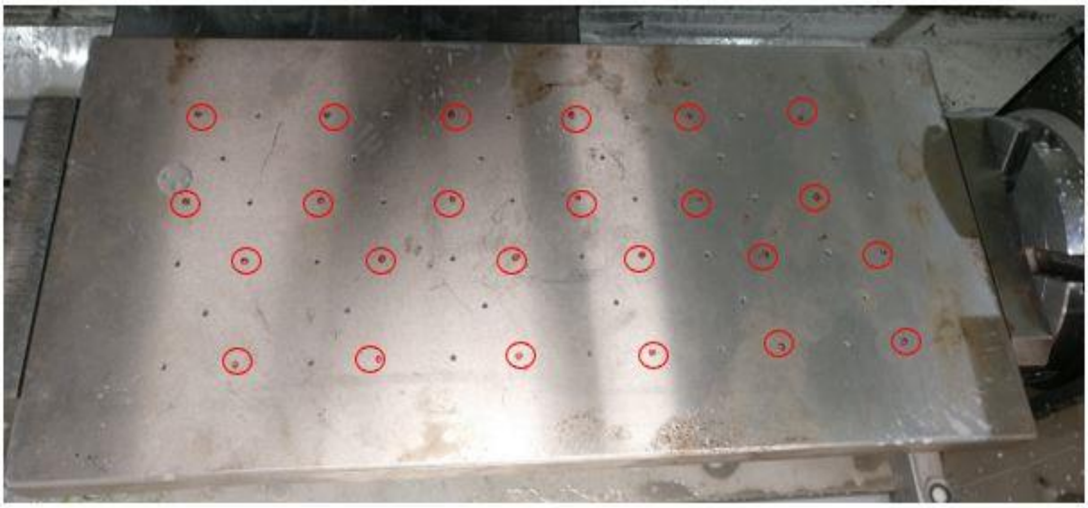
In Table 44 is the list of operation carried out in machining the A-Pillar rotatory support.

Table 44 - Operations and the timing in machining of the A-Pillar rotatory support.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (min)
1	Face Milling	20	30
2	Profile Milling	20	70
3	End Milling	20	90
4	Drilling	8, 10.25, 13 and 17	10
	Total time		**200**

3.10.4 Base plate

The base plate was one of the main components that was outsourced due to the unavailability of clamping for a steel plate of size 540 mm (L) x 240 mm (B) x 30 mm (H). The main milling vice used can only hold parts for small dimensions. Once, the jig was ready and assembled with the side supports it was mounted in the CNC table and a drill for 11.5 mm was done for easy mounting and unmounting of holding and clamping pins in case of failure. Figure 85 shows the how the drilling operation was carried by assembling the skeleton of the jig.



(a)

(b)

.

Figure 85 - (a) In this image the point circled in red showing incorrect marking points (b) Holes drilled for diameter 11.5 mm.

In Figure 85 (a) the circled red points are incorrect due to a mistake made in calculating the coordinate points in the CNC program. This stresses on the fact that how important in trial runs of the program, a shadow running and running the spindle at a higher/safer Z-value to check for any unusual line of code or any interference could be caused at normal operation. It highlights the patience process that's required in machining new parts. Listed in Table 45 are the peck drilling diameters that were carried out and its timing for those drillings.

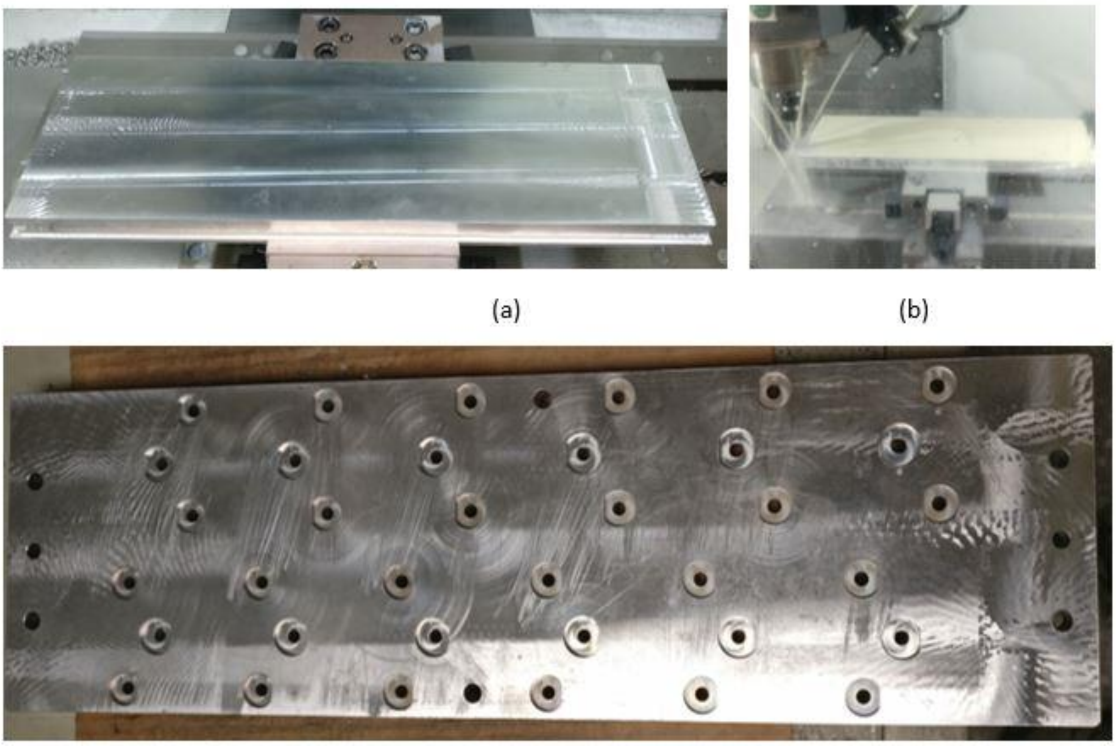
The design for holes at the back of the base plate was done keeping in mind to unscrew the screws in the main plate if a situation arises where one needs to replace the holding pins or support pins.

Table 45 - Peck drilling dimension and its timing for the base plate.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (min)
1	Marking	4	10
2	Peck Drilling	8 and 11.5	70
3	Chamfer	17	10
	Total time		**90**

3.10.5 Main Plate

The main plate or called aluminium plate on the machining floor was the easiest machining material to work with and hence used higher machining speeds. It was also the one that took a lot of machine time due to the pocketing that’s needed for holding the pins. Figure 86 shows few of the milling process in the making. It all started with a block of aluminium 6061-T651 of dimension 560mm (L) x 180mm (B) x 25mm (H).



(a) (b) (c)

Figure 86 - (a) Exterior profiling (b) Exterior profile milling in action (c) Machined the main plate and cleaned.

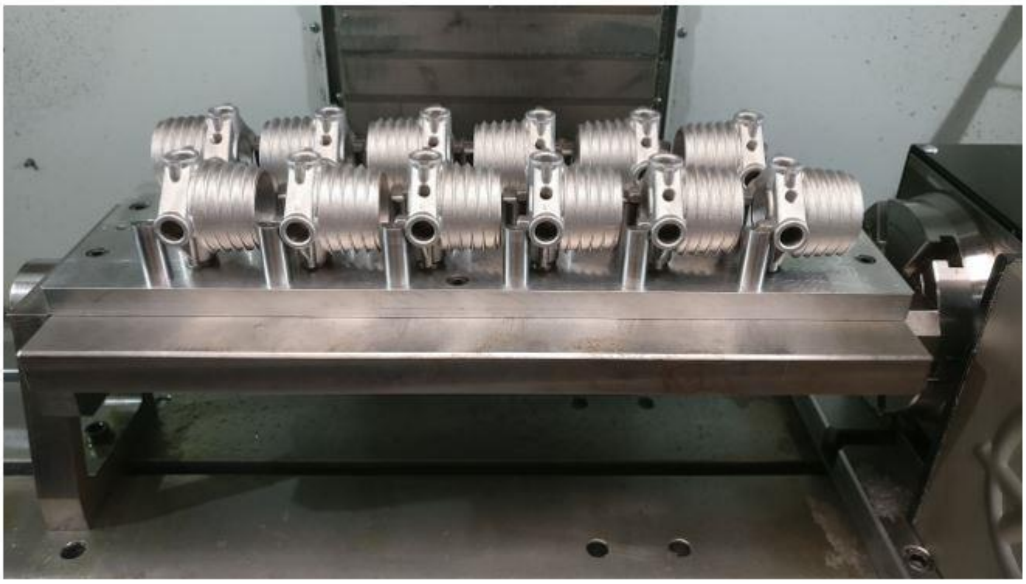
In Table 46 is the list of operation carried out in machining the main plate.

Table 46 - Operations used and timing in machining the main plate.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (mins)
1	Face Milling	63	43
2	Profile Milling	20	300
3	Pocket Milling	6	180
4	Drilling	6 and 9	180
5	Boring	6	30
Total time			**713**

(a)

(b)



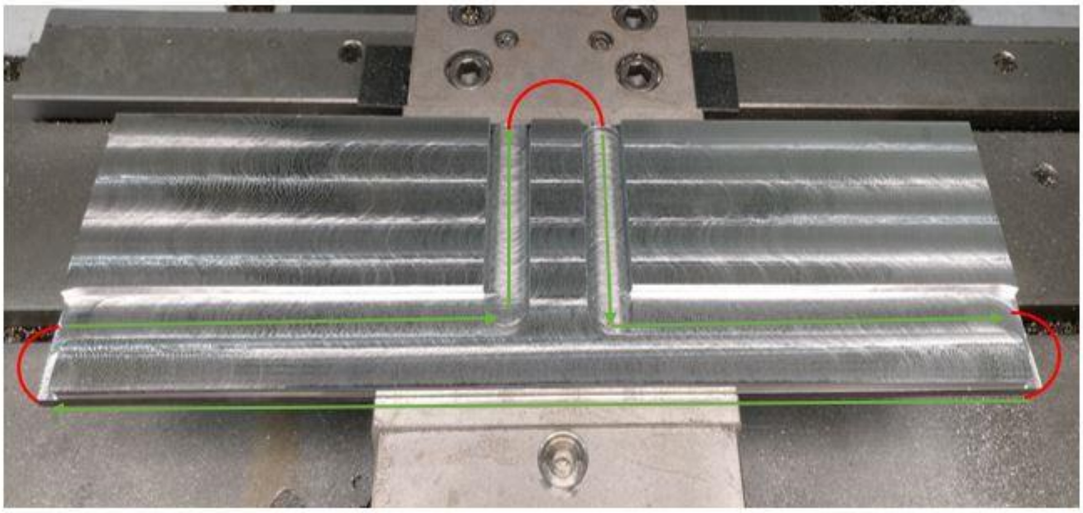
(c)

Figure 87 - (a) Holding pins shaped using sandpaper for a sliding fit (b) Holding and support pins being assembled in the main plate (c) Main plate withholding and support pin fit check by testing with parts on the skeleton.

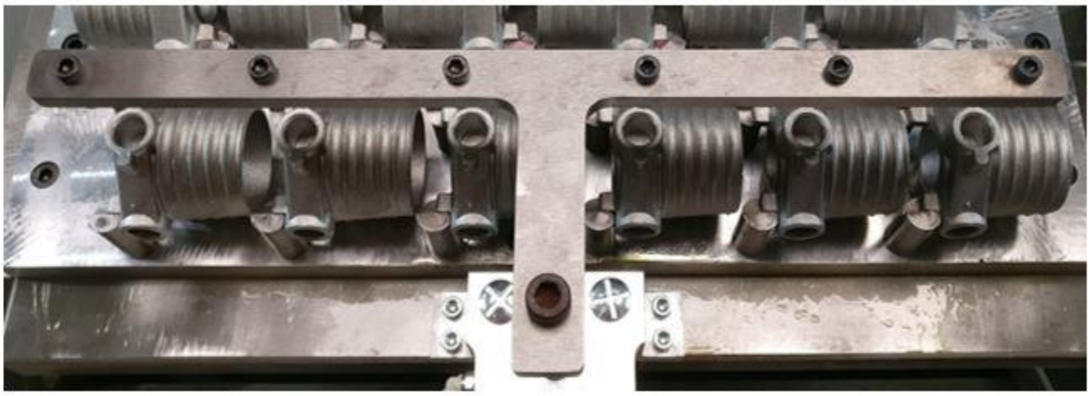
The process of finding the perfect fit was a continuous improvement process based on the test runs and disassembling the jig to sand the pins. Also, making the pins conical was important in achieving the fit. Even a misalignment by 1/10 of a millimetre can cause the parts at the end of the clamping arm to move vertically. The process images are shown in Figure 87.

3.10.6 Clamping Arm

The clamping arm was the thinnest part to be machined, hence had to deal with a lot of vibration on machining at the end. The block of steel used machine was of dimension 411 mm (L) x 120 mm (B) x 12 mm (H). For this jig, two clamping arms were required. The tool path in the creation of the clamping arm is highlighted in Figure 88.



(a)



(b)

Figure 88 - (a) Tool path over the block of steel creating the exterior shape (b) Clamping arm attached to the pneumatic cylinder.

In Table 47 is the list of operation carried out in machining the main plate.

Table 47 -Operations used and timing in machining the clamping arm.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (mins)
1	Face Milling	20	40
2	Profile Milling	20	72
3	Marking	1	5
4	Drilling	6.5 and 10.5	12
	Total time for one arm		**129**
	Total time for two arms		**258**

3.10.7 Pneumatic Cylinder Holder

The cylinder holder was decided to be made from the aluminium raw material used in die casting - AlSi9Cu3 (AL6061-T4(SS)). It was an accessory that was designed as the last component to be machined and the wait for steel dint justify its purpose. Hence the use of raw material that was available inside the company was preferred is shown in Figure 89.

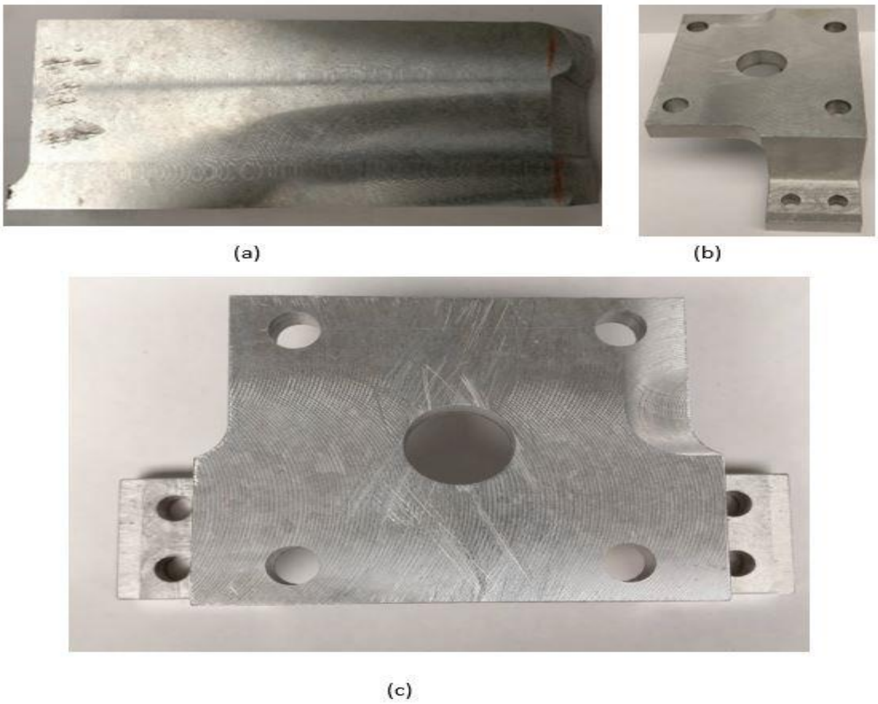


Figure 89 - (a) AlSi9Cu3 raw material used in die casting been faced (b) Side view of machined part (c) Top view of the part.

In Table 48 is the list of operation carried out in machining the main plate: -

Table 48 -Operations used and timing in machining the pneumatic cylinder holder.

S. NO	TYPE OF OPERATION	TOOL DIAMETER (mm)	TIME (mins)
1	Face Milling	63	20
2	Profile Milling	20	124
3	Drilling	6.5 and 10.5	20
	Total time for one arm		**164**
	Total time for two arms		**328**

3.11 Operation study

In this section, one can understand how the new jig operates and what kind of new process is employed in making the jig more efficient than the previous one.

3.11.1 Jig implementation

The implementation phase was the most exciting and fruitful phase of this project. The implementation phase could be divided into a few smaller phases. Some of these phases are listed below: -

- Selecting the right tool for the jig.
- CNC coding phase.
- Creating work procedures to reduce setup times.

3.11.2 Selecting the tool and their holders

One of the challenging parts about new jig its tight angle to work without any interference. A new type of tool holder was needed to machine parts with the relatively good amount of space around the tool. The tools used are the same as the previous jig (refer to Table 9), it’s only the holder that changes. A detailed sketch and picture of the new tool holder used are shown in Figure 90.

(a) (b)

Figure 90 (a) New tool holder of SK 40 specification (b) New tool holder used in finding Z-levels for machining.

3.11.3 CNC coding phase

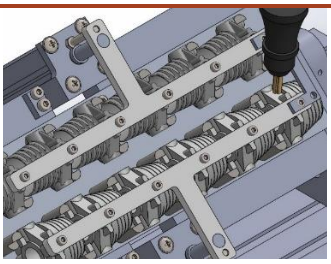
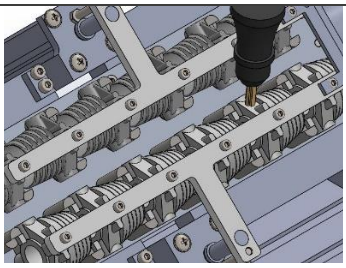
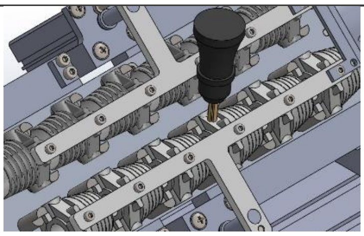
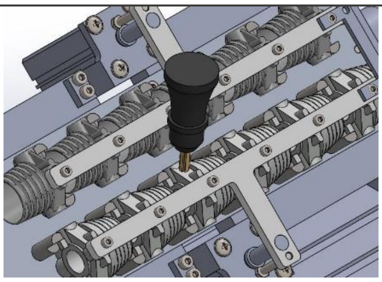
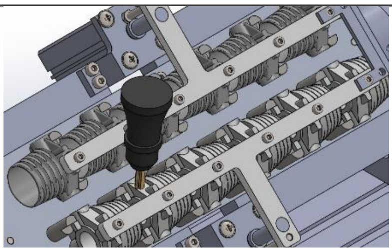
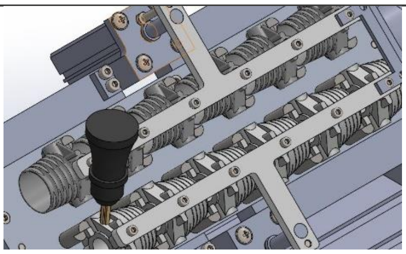
As seen in section 2.6.4, concerns were raised on the high tool air time. which is a waste of movements that could be improved for optimization. The design of the new jig incorporated these inputs in producing the final product.

A part of the new sets of G-codes used in machining Winding Cone_1 is listed in Table 49 emphasising its efficiency. It would not possible to put the entire code as its intellectual property of the company. And the sequence e of the drill is illustrated in Table 50.

Table 49 - The new sequence G-code for the new jig.

DRILL SEQUENCE	G-CODE	DESCRIPTION
0	**G00 Z-77;**	Rapid motion to just 5mm above the first drill spot.
1	**G81 G98 Z-102 F1000;**	Drill cycle starts with an endpoint in Z at -102 with a feed rate of 1000mm per minute
2	**X-79;**	The next point to travel in X-axis with rapid motion
3	**X-153;**	The next point to travel in X-axis with rapid motion
4	**X-227;**	The next point to travel in X-axis with rapid motion
5	**X-301;**	The next point to travel in X-axis with rapid motion
6	**X-375;**	The next point to travel in X-axis with rapid motion
0	**G00 G80 Z110 A-102.8;**	Drill cycle ended, and the spindle rises up to a safe distance and the 4th axis rotates to -102.8 degree.

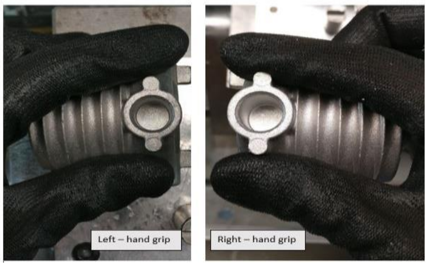
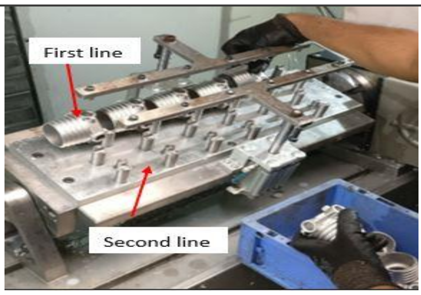
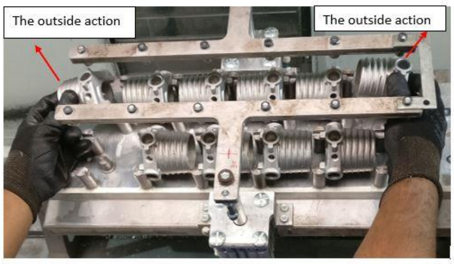
Table 50 - Illustration of the drill cycle shown with the help of CAD images.

ILLUSTRATION OF THE DRILL CYCLE MENTIONED IN THE PREVIOUS Table 49	DRILL SEQUENCE
	1
	2
	3
	4
	5
	6

3.11.4 Creating work procedures

The new operation principle for the new jig is detailly listed in Table 51. This helps in reducing the setup time further adding to the overall efficiency of the machining process.

Table 51 - New machining cycle procedure.

DIAGRAM	SEQUENCE OF STEPS
	**Step 0** - Firstly, the new process needs 2 baskets. One fully loaded with 12 unmachined parts (Winding Cone_1). Another empty one to unload the machined parts.
	**Step 0** – The grip that's required for faster loading of parts. This also a part of the loading procedure. The thumb and index finger are always resting on the sides to be machined.
	**Step 1** – Loading the part from the back of the jig. This helps in reducing the load time of the part. And then the second line is loaded.
	**Step 2** – Once the machining cycle is finished. The parts are removed in the outside action.
	**Step 3** - This is an optional procedure. Especially this design eliminates the need for cleaning with an air nozzle.

There are other non-value adding steps like cleaning the machined parts. Which is similar in both jigs.

3.11.5 Collecting setup time and operation time

The collection of cycle time in the new jig was done exactly like the previous one with a sample of 10 cycles after a few warm-up cycles. The cycle time collected is defined as the time taken between two consecutive press of start button. The collected cycle time is mentioned in Table 52.

Table 52 - New cycle time collected using the new jig for 12parts.

SAMPLE NUMBER	CYCLE TIME (min)	CYCLE TIME (s)
1	03:25.2	205
2	03:26.2	206
3	03:41.5	221
4	03:12.4	192
5	03:16.8	196
6	03:30.2	210
7	03:19.8	199
8	03:27.6	207
9	03:34.6	214
10	03:17.8	197
Average cycle time		**204.7**

As mentioned in previous sections the procedure is very simple and similar to the previous jig procedures. The cycle time for 12 parts was 204.7 seconds in the new jig. A visual stream map (VSM) of the procedures that happen during the cycle time is mentioned for the new process in Figure 91.

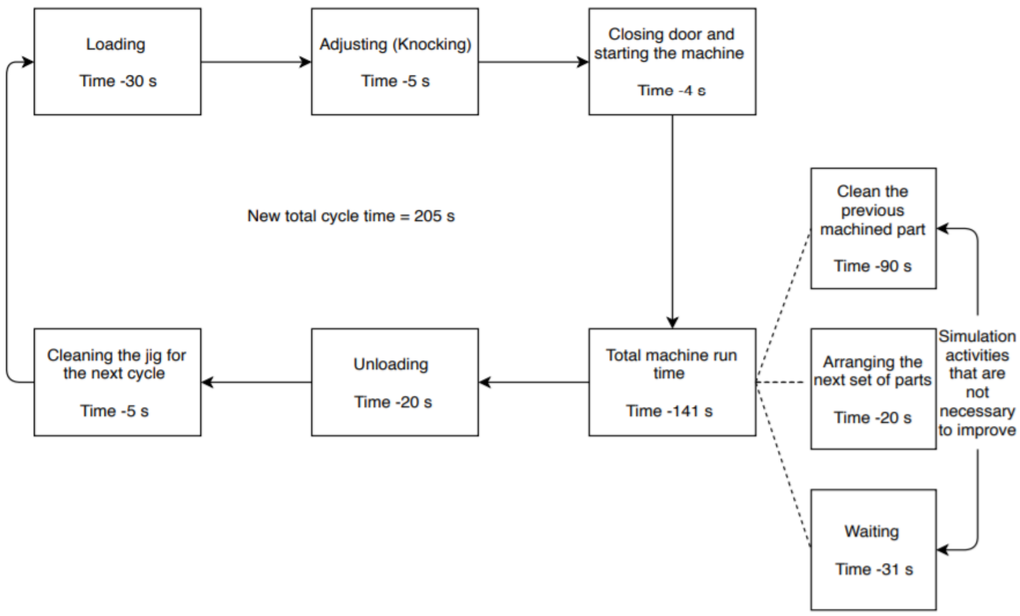


Figure 91 - Visual stream mapping (VSM) of the entire machining process in the new jig for 12 parts.

3.11.6 Critical analysis of the system implemented

It is part of the *verify* phase in DFSS methodology. The critical analysis is carried out in 2 stages one about the design and other about the overall process improvement using metrics like PCE. The standard used in this project for analysing the design was SWO analysis as shown in Table 53 and Figure 92. The same is used in giving one comparative analysis for the new jig implemented.

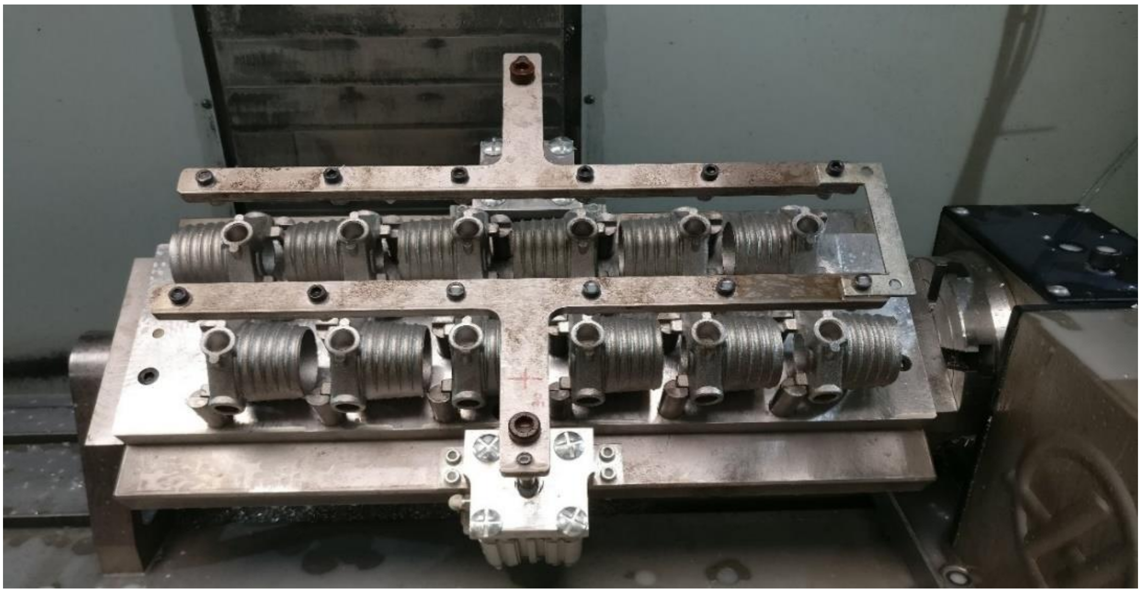


Figure 92 - A picture of the new jig in between the machining process.

Table 53 - SWO analysis of the new jig.

STRENGTH	WEAKNESS
• The rectangular shape of the jig makes it easy and faster machining for a process that requires drilling. • Better clamping for parts. • Doesn't require cleaning with an air gun (but although it is advised to clean after a few cycles). • Visual check and poke yoke are an inbuilt feature of the jig. Hence, it is very easy to load the part without any mistake. • Multi-functionality of the jig helps in using it for machining other parts.	• Very heavy compared to the previous jig. • Expensive than the previous jig. • Requires safer distance from the jig for a tool change. • Loading part is cumbersome for amateurs. • Setting up is generally tiresome and requires another person to help in the process.
OPPORTUNITY	
• Increasing the stroke length of the cylinder in future for better hand movements • Try to modify the pneumatic cylinder position to help machine Winding Cone_2 parts (But discontinuing procedure in progress).	

The process improvement metric is explained in Table 54 and Table 55 by comparing based on the data collect and forecast with some realistic assumption. For example, the total machine time available per day in seconds is 52200 seconds based on a 14.5 hours total available operation time.

Table 54 - Critical analysis -1 of performance metrics.

METRICS	OLD JIG WITH 8 PARTS	NEW JIG WITH 12 PARTS
Total Cycle time (s)	179.5	204.7
Total machine time (s)	129	141
Setup time (s)	50	64.7
Time per part (s)	22.4	17.1
Total tool change (units)	2	2
Tool change time (s)	1.6	1.6
Number of cycles in an hour (cycles)	19	17
Number of parts machined in an hour (units)	152	204
The number of machined parts increased in an hour (units)	52	

Table 55 - Critical analysis -2 with cost savings.

METRICS	OLD JIG WITH 8 PARTS	NEW JIG WITH 12 PARTS
PCE (%)	72% for 8 parts	69% for 12 parts
Number of parts that can be machined per day (units)	2320	3060
Optimization using the new jig (%) = (Difference in number of parts produced using new jig per day)/(Total parts in the old jig per day)	32% (approx.)	
Total number of machining hours that could be potentially saved per day = {(22.4*52)/60}*14.5	281 minutes / 4 hours 41 minutes (approx.)	
Based on forecast (Figure 45**), total cycle required to fulfil in 2019 (cycles)**	10881	7254
Total number of cycles that could be saved in 2019 (cycles)	3627	
Total cycle time that could be saved in 2019 (hours) = {(179.5*3627)/(60*60)}	180.85 (approx.)	
Machining operation cost (based on cycle time) that could be saved at €35/hour for the next years forecast (€)	6329.6 (approx.)	

From Table 54 one can conclude after comparing the initial and improvement data. A 32% increase in the number of parts machined in an hour. This could lead to a potential saving of more than €6000 a year by using the new jig. A video of the old jig and new jig working is upload in YouTube to visually see the implementation. The corresponding link is mentioned below: -

https://youtu.be/88vGhZhd5D0

3.11.7 Ergonomics of the jig

This was a crucial part of the issues found in the initial study by working with the old jig. due to its circular shape and the direction loading the parts in the X-axis of the CNC table (refer Figure 46). The operator working on the CNC generally move their arm around the Y-axis and hence, creating an uncomfortable position in the loading process of the parts in the jig especially on the lower part of the jig.

(a)

(b)

Figure 93 - (a) loading the part with hands hitting the clamps and other parts of the jig (b) Easy and minimalistic interference of the jig near the loading area.

From Figure 93 one can see and understand the difference in work posture and positions of the loading/unloading using hand. The general review for the operators of the 2 shifts liked the convenient of loading/unloading the parts in front of them instead on the side. Which they consider it to be a hindrance.

3.11.8 Payback calculation

Based on the total cost spent in making the new jig, the payback period required to earn the investment back. The payback period is calculated using the formulae mentioned in the section 2.4.5Principles of industrial costing and payback. the summary is listed in Table 56.

Table 56 - Payback period summary.

Investment (€)	3047.16
Return (Per annum estimation in €)	6329.6
Payback (months)	6 (approx.)

3.12 Modularity of the Jig

At the start of the project, the main feature to be implemented in the new jig was to make it with modular function. There were various designs with the feature of modularity in it. But later iteration just concentrated on making a fixed jig or one single purpose of machining Winding Cone_1.

When thinking of making a fixed design, there was an emphasis on making modular components and assembling a fixed design. Later during the project phase was when one had the opportunity to make a jig for a different part (called as `*small part*´ for reference). The specification and detail of the part of the jig made for that part cannot be published in this report as part of company information use policy. But visual cues of the part and how the current jig skeleton (used to machine Winding Cone_1 and also refer to Figure 85) was used in making a new main plate. Illustration of the part and final jig for the `*small part*´ is shown in Figure 94.

The part requires only a drill on one of its sides. From an economic point of making a jig for this part was making it as inexpensive as possible. The deadline was very short to the machine and deliver the parts to the client. Hence using the knowledge and resource (the already built skeleton, G-code and material selection) made such a difference that before one could get the improvement data of Winding Cone_1 jig implementation, one had already delivered some fractions of the `*small part*´ order to the client.

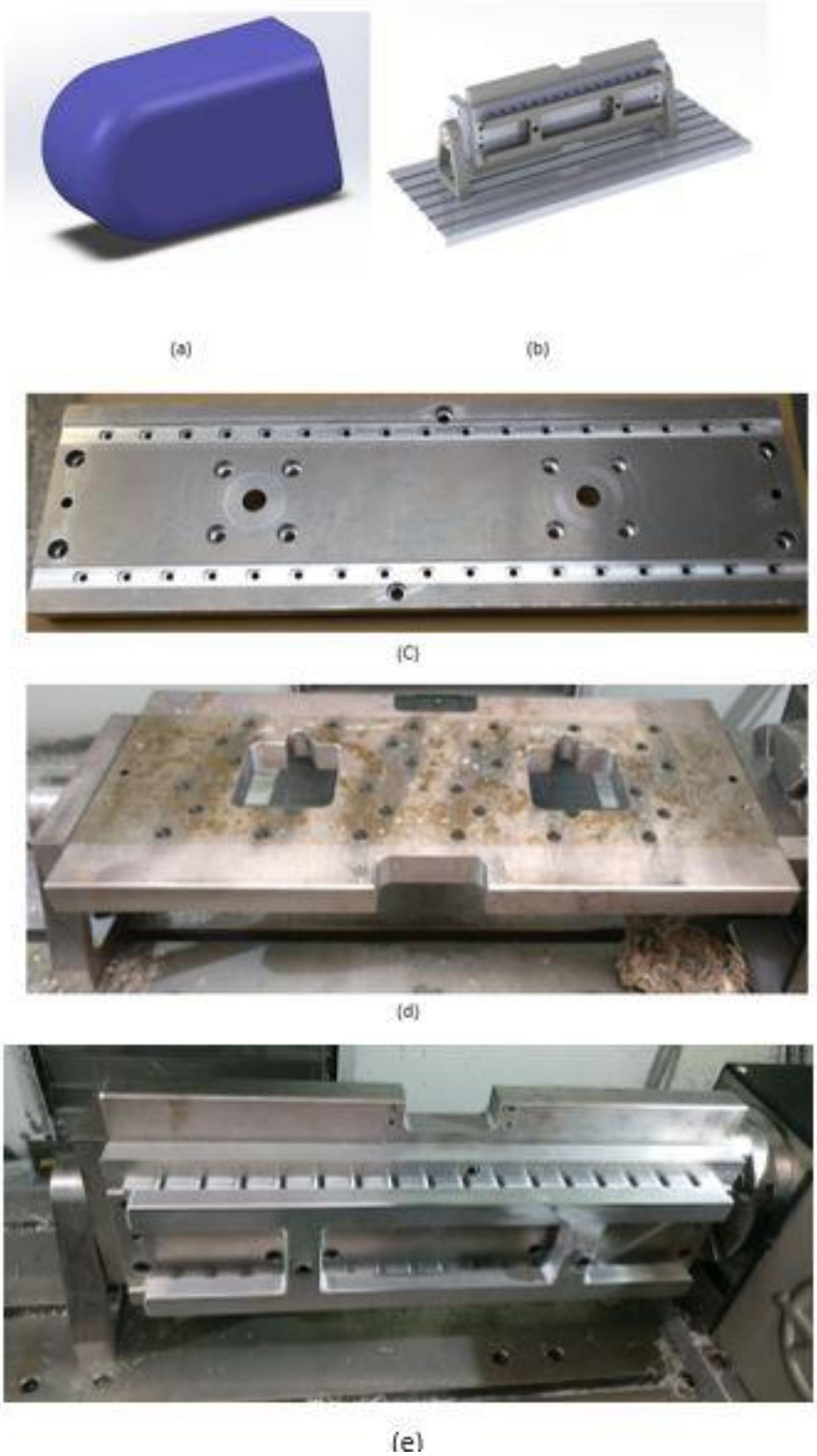


Figure 94 - (a) The small part in 3D CAD (b) Full assembly rendered in SolidWorks (c) Machined the main plate of the dimensions of the main plate for Winding Cone_1 (d) Skeleton of the jig modified to machine the small part (e) Working jig for machining the small part.

CONCLUSIONS AND PROPOSALS FOR FUTURE WORKS

4.1 Conclusion

4.2 Skills gained during the project

4.3 Proposal for future works

4 CONCLUSIONS AND PROPOSALS OF FUTURE WORKS

4.1 Conclusion

In this thesis for continues improvement of machining process of the product Winding Cone_1. Working with the previous jig for 8 parts, showed that there were possibilities in reducing the machine time per part. By analysing various data acquired in the initial *analyse* phase of the DFSS approach that was followed in the project. Various quality, process improvement tools and along with SolidWorks CAD models, key factors were marked into the requirements of the project. The PCE was found at 72% but reduced takt time of 24.2 seconds for 2019 (forecasted) justified the estimated spending for the new jig with more than 8 parts per cycle.

The development phase was the most complex part. The design iterations and the manufacturing standard component of the jig were happening simultaneously in-house during this phase. A SWO analysis was implemented in analysing each iteration of the design. SWO analysis is a design version of regular SWOT analysis, since threat is not applicable in analysing using the SWOT tool. Finding solutions for clamping, trying to make the jig a modular system and ultimately trying to reduce the cycle time. The final iteration was confirmed to have 12 parts per cycle. The material selection was finalised based on high tensile and low cost of Aluminium 6061-T651 and AISI P20+S. It took extensive planning in machining and more than 43 hours of timed milling of components. Once the jig was finished and new cycle time was recorded to be compared. The critical outcome of the comparison is listed below: -

- Built a working jig in-house with 12 parts per cycle with the maximum utilization of the CNC table. The new jig design and fabrication allowed comfortable loading and unloading of parts.
- Total machining process efficiency was increased by 32%. This was a combination of making the jig in a foolproof (Poke-Yoke) design helped in reducing the setup time. Hence, reducing machining time per from 22.4 seconds to 17.1 seconds.
- The PCE was reduced to 68% for the new jig from 72% of the old jig. But it’s should be noted that the new jig makes 4 more parts per cycle. Still, the metric PCE indicates that there is a possibility in reducing the setup time for the new jig.
- The efficiency results in more than 4 hours of saving per day in machining Winding Cone_1. With a total saving of more than 180 hours in machining the forecasted parts. The savings in time could result in savings of more than €6000

per annum and recovering the cost of the jig in less than 6 months. Table 57 has a simple checklist of all the goals achieved that were set at the initial stage of the project (refer section 3.3.2).

Table 57 - Checklist of goal achieved from initial requirements of the project.

GOALS SET AT THE START	RESULT	CHECK (✗/ ✓)
Design and create jig with more than 8 parts per cycle.	The outcome of the project was a working jig with 12 parts per cycle.	✓
Try to use the maximum length of the CNC table available.	Used 630 mm of the usable 750 mm of the CNC table.	✓
Jig design that minimizes tool air time.	Visual inspection reveals reduced tool airtime than the previous design.	✓
Reduce cycle time per part.	Cycle time per part was reduced from 22.4 seconds to 17.1 seconds.	✓
Better ergonomics.	Achieved better ergonomics for loading and unloading (refer to Figure 93).	✓
In-house fabrication of the jigs modular components.	Machined 7 of the 11 necessary components in-house for the new jig.	✓
Design and machine a modular jig system.	At the time of finishing this project, it was used to machine 2 different products and ideas for machining various other products were also in place.	✓
Create a jig with less weight possible than before.	The purpose of the new jig is heterogenous now. Hence, weight reduction was not possible as cost had to be low as possible for maximum strength.	✗

4.2 Skills gained during the project

In the course of this project, my learning about machining has widened in particular, how to design with manufacturing and machineability in mind. I have also worked hands-on in machining various different product at the company, helping me in understand the basics of CNC machines, setups and process improvement tools.

Working on this has definitely help walkout from the internship with a better design approach to manufacturability.

Also, another important aspect of this project that could not be possible to learn in the classroom is the work culture in an SME in Portugal, which differs from my home country. I was able to gain valuable insight into the work ethic and attitude that is required in future opportunities in Portugal or any other workplace as matter of fact. A detailed evaluation of my performance, jobs are undertaken, and conduct is attached in ANNEX4 as a form of intern performance evaluation letter.

4.3 Proposal for future works

The future works of this project are listed below: -

1. Adjusting the current pneumatic cylinder position to a lower level that will help in machining Winding Cone_2.
2. Another bigger diameter winding cone is also produced and machined with similar procedure and tools. The current jig machines 6 parts per cycle. With the same skeleton of the jig and another main plate for the bigger winding cone could optimize the number of parts per cycle.

REFERENCES AND OTHER SOURCES OF INFORMATION

5 REFERENCES AND OTHER SOURCES OF INFORMATION

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ANNEXES

6.1 ANNEX1

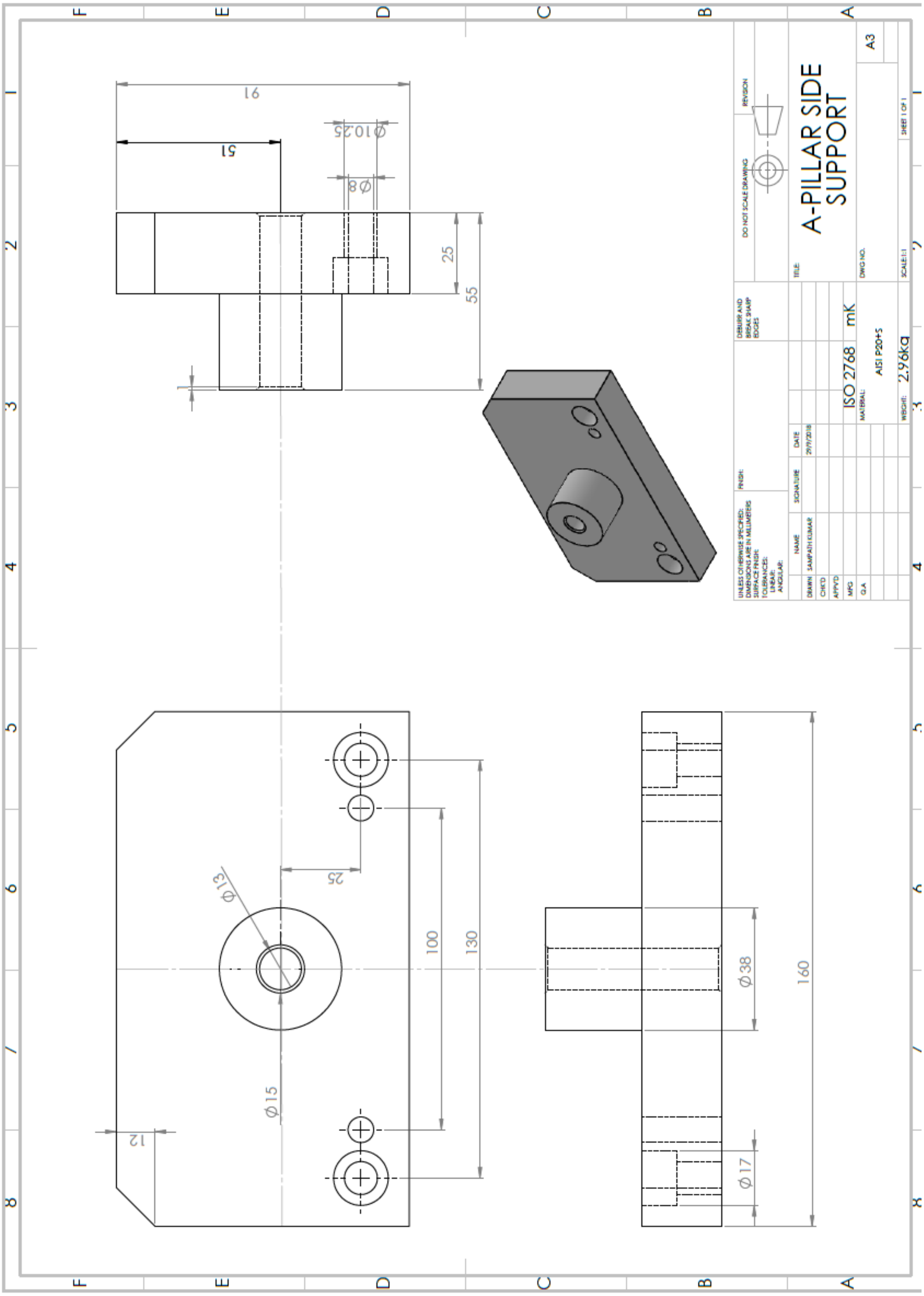
6.2 ANNEX2

6.3 ANNEX3

6.4 ANNEX4

6 ANNEXES

6.1 ANNEX1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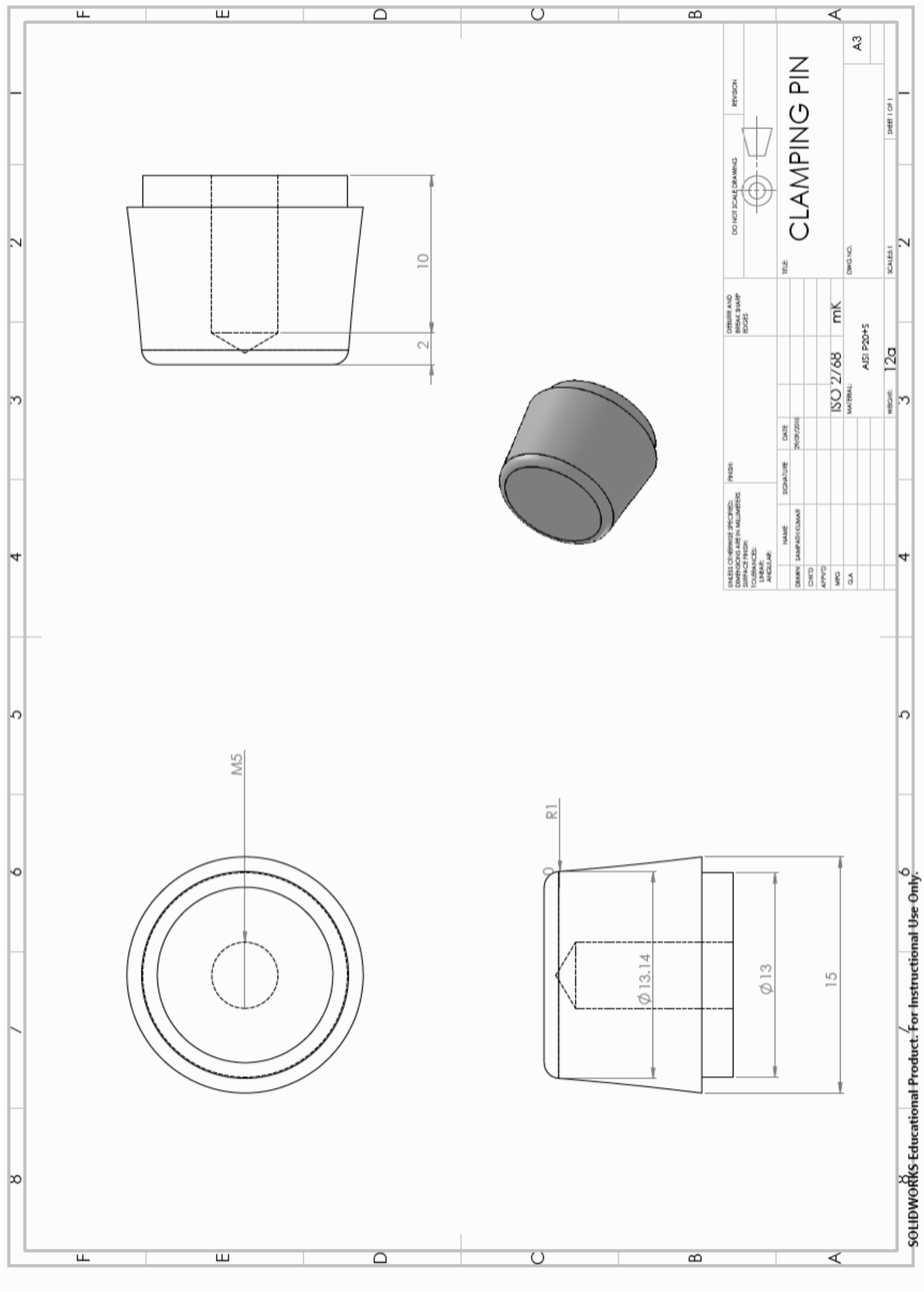
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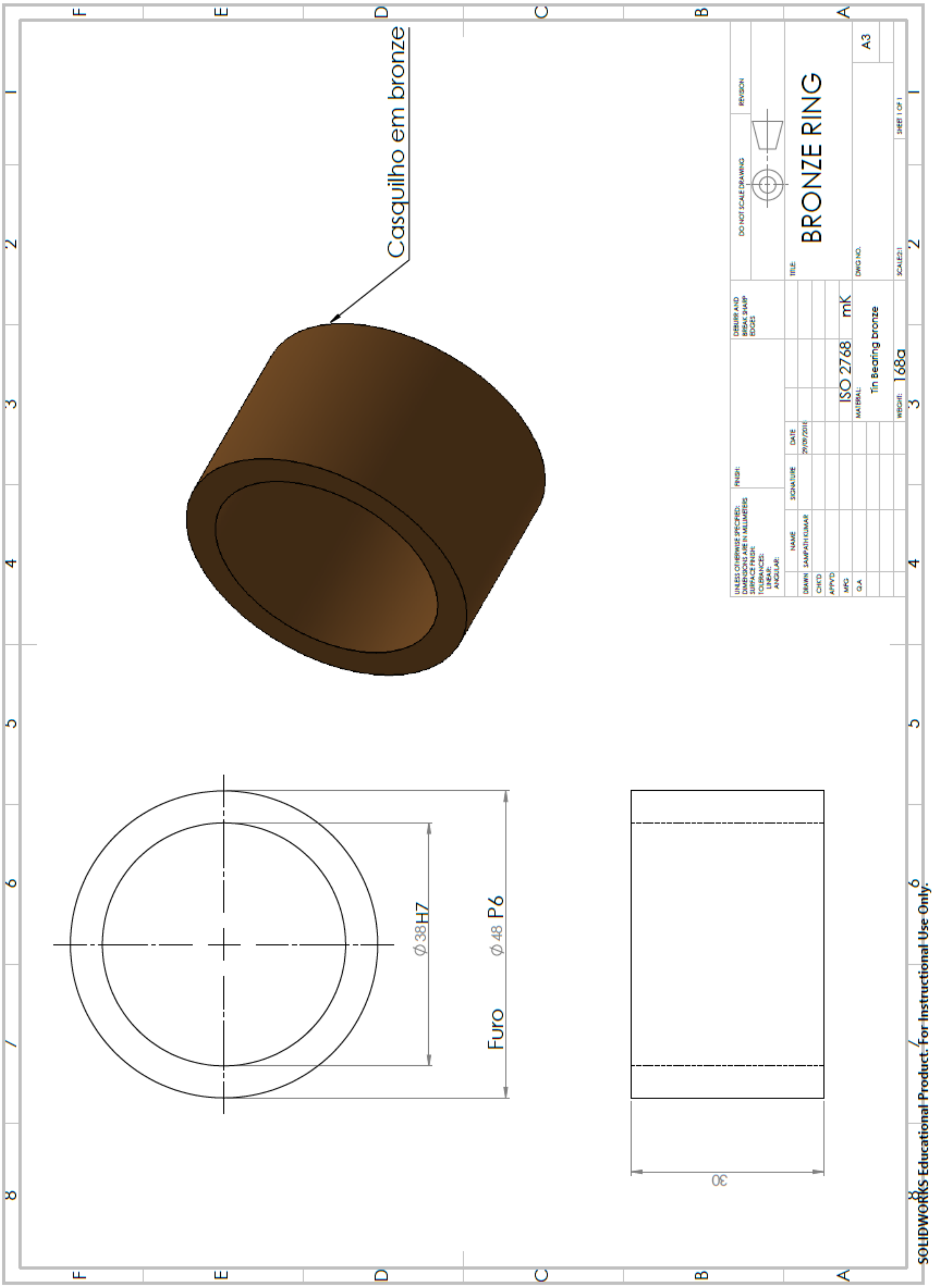
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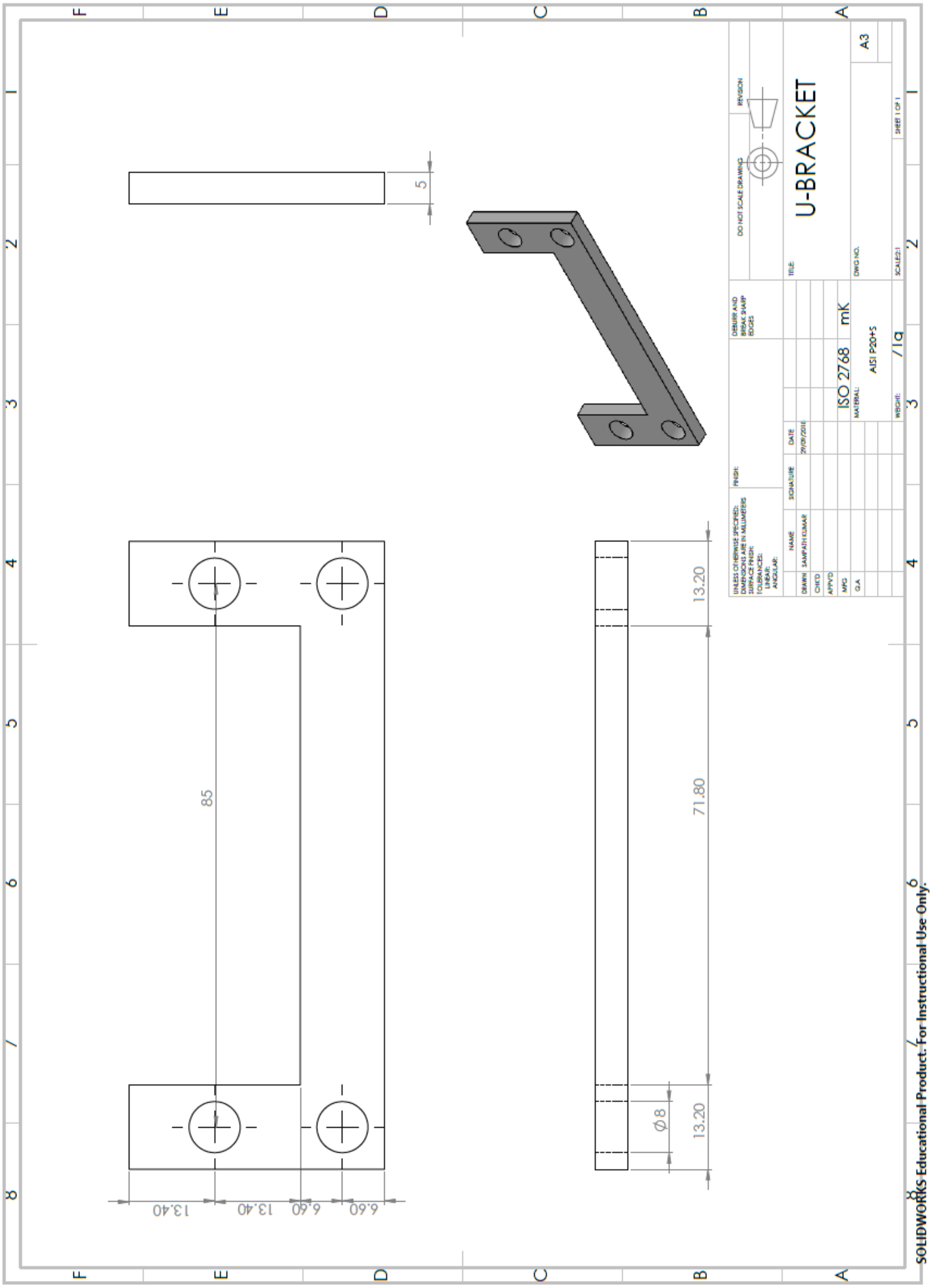
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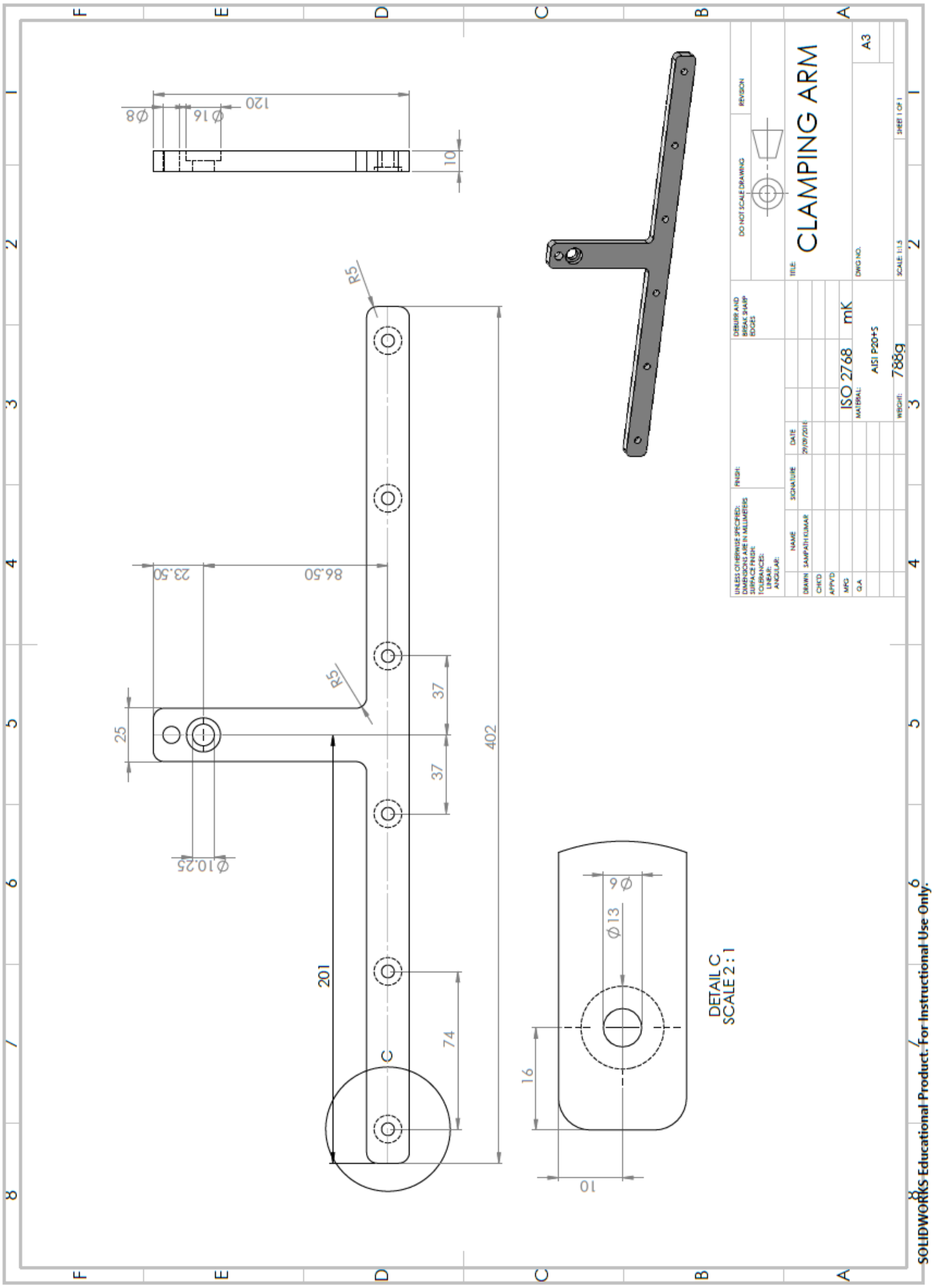
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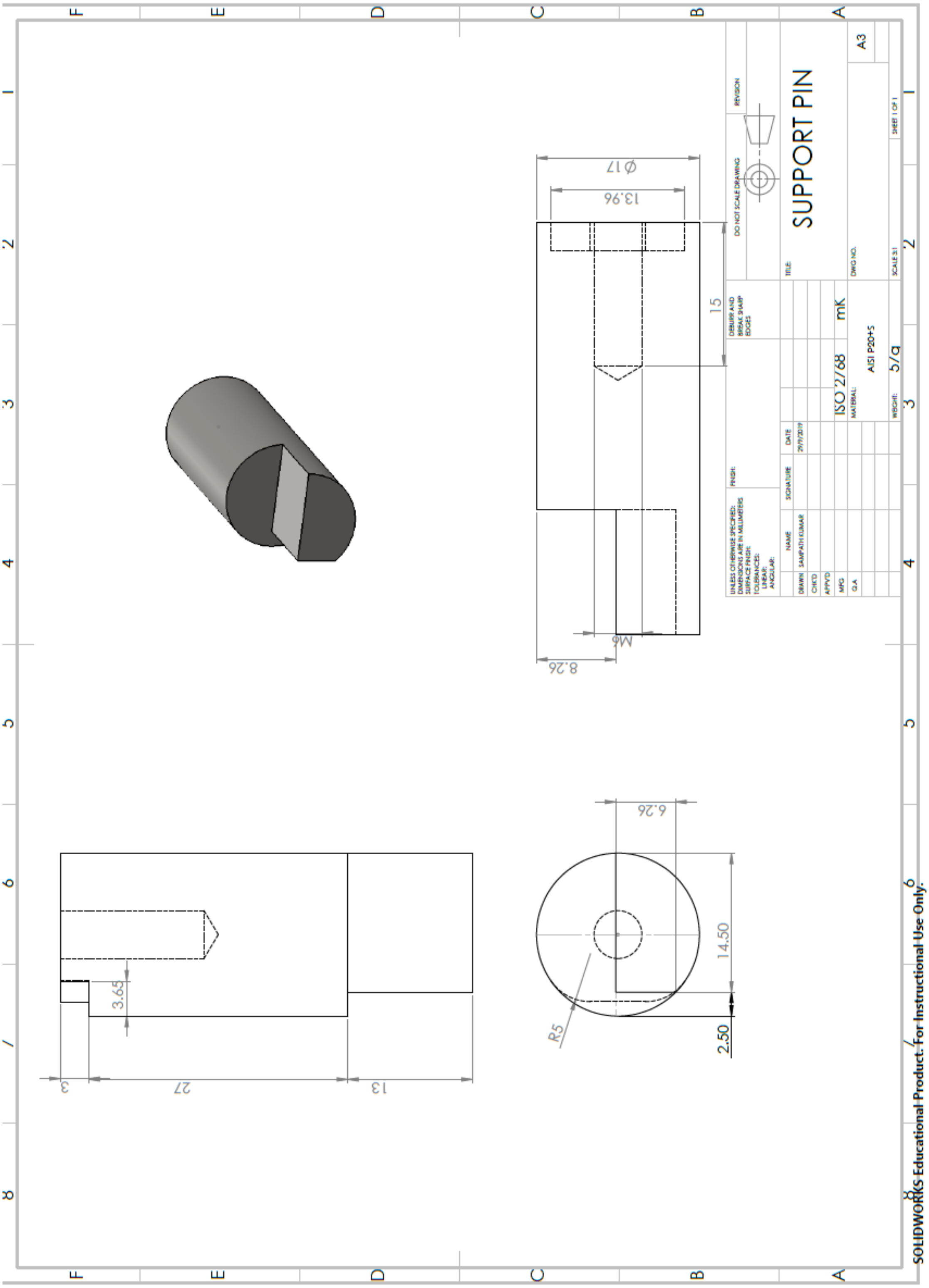
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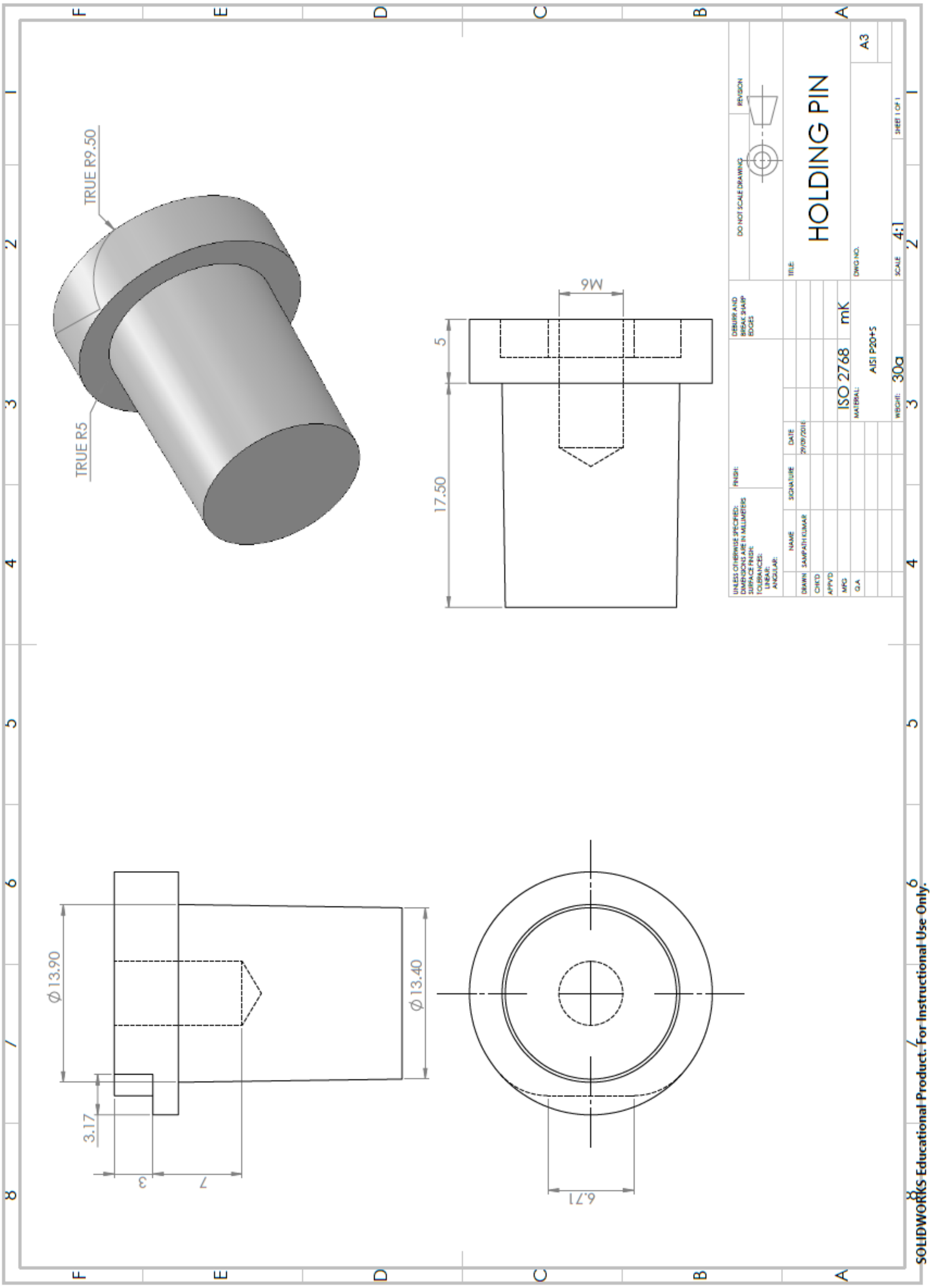
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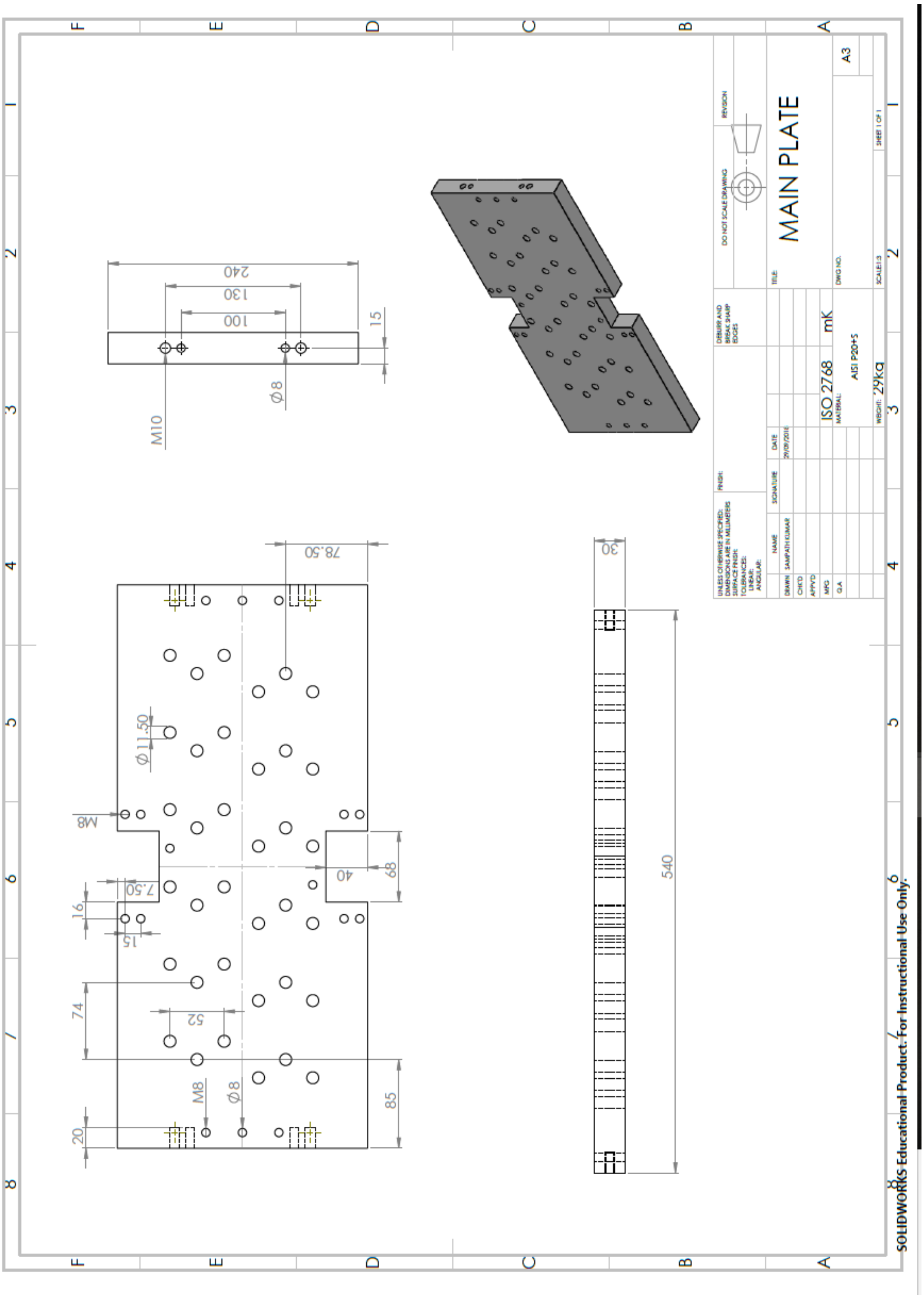
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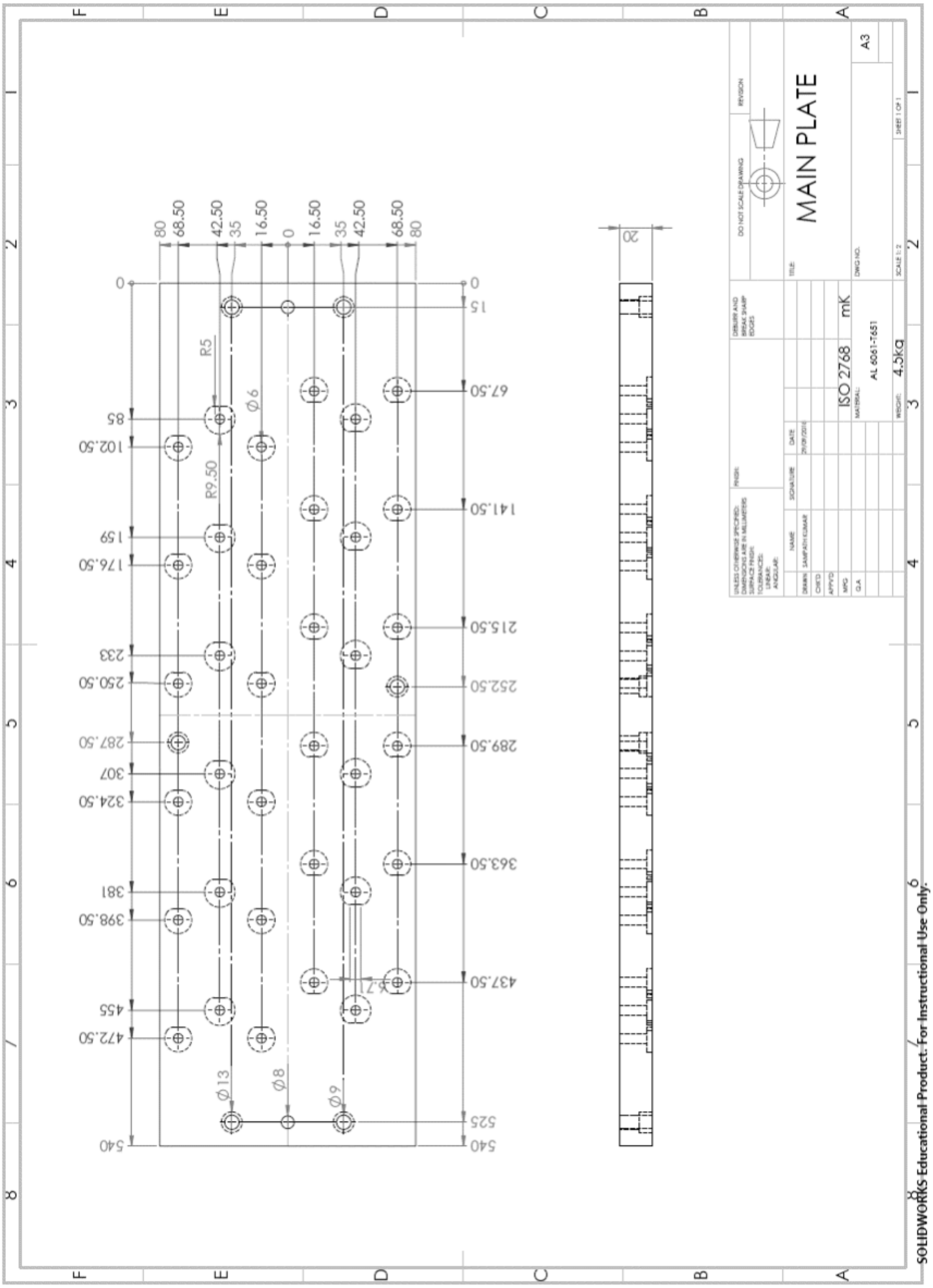
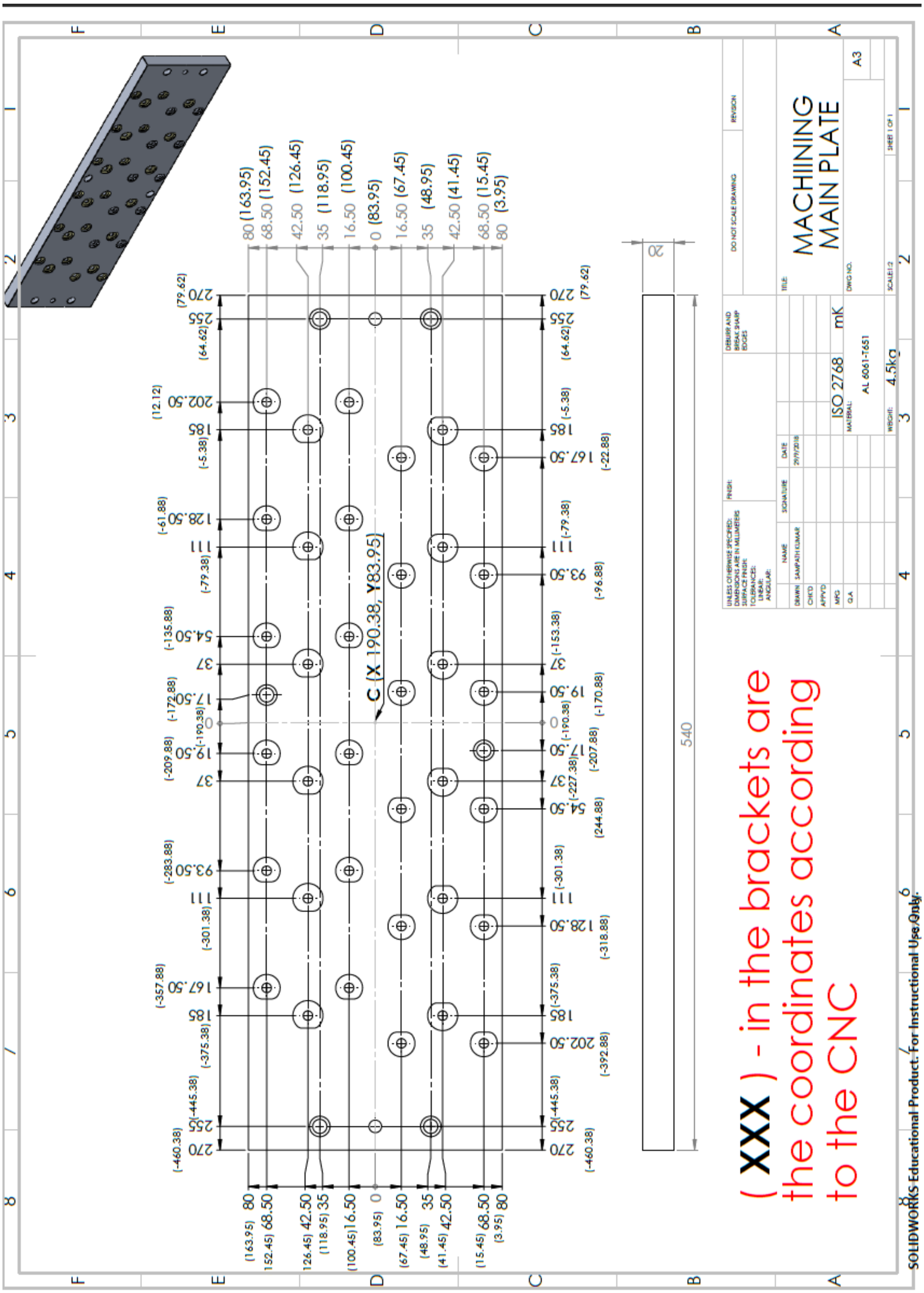
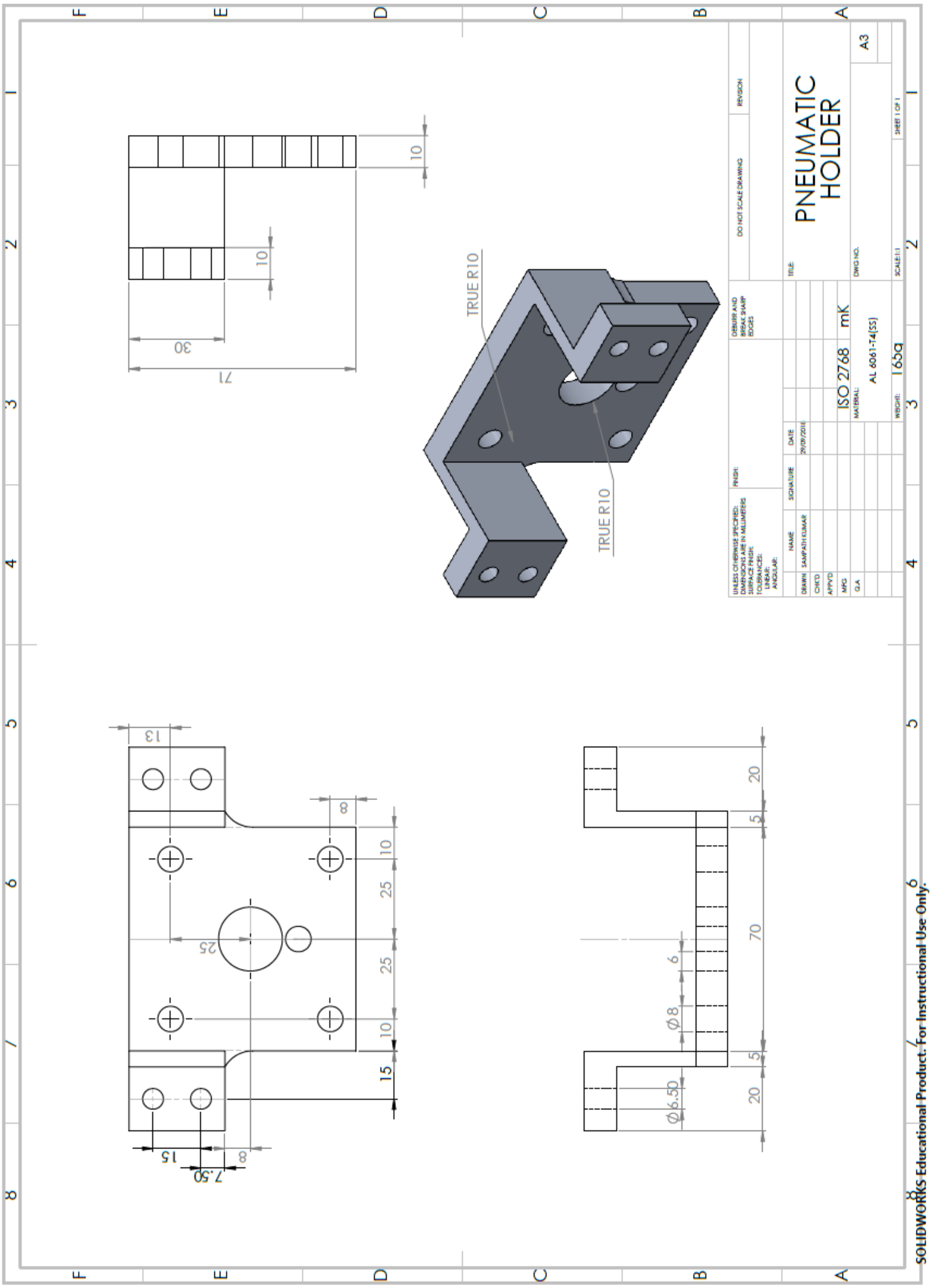
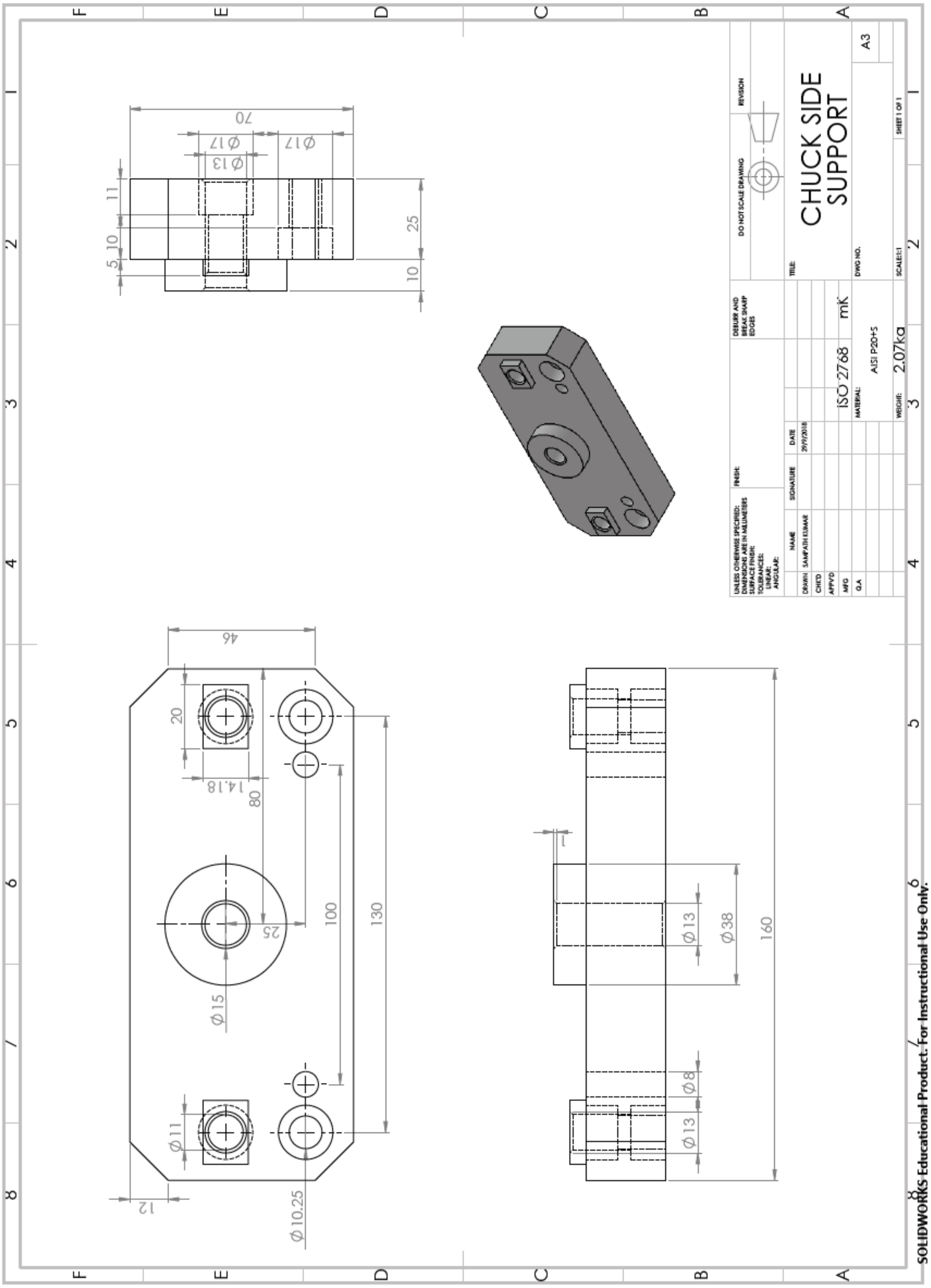
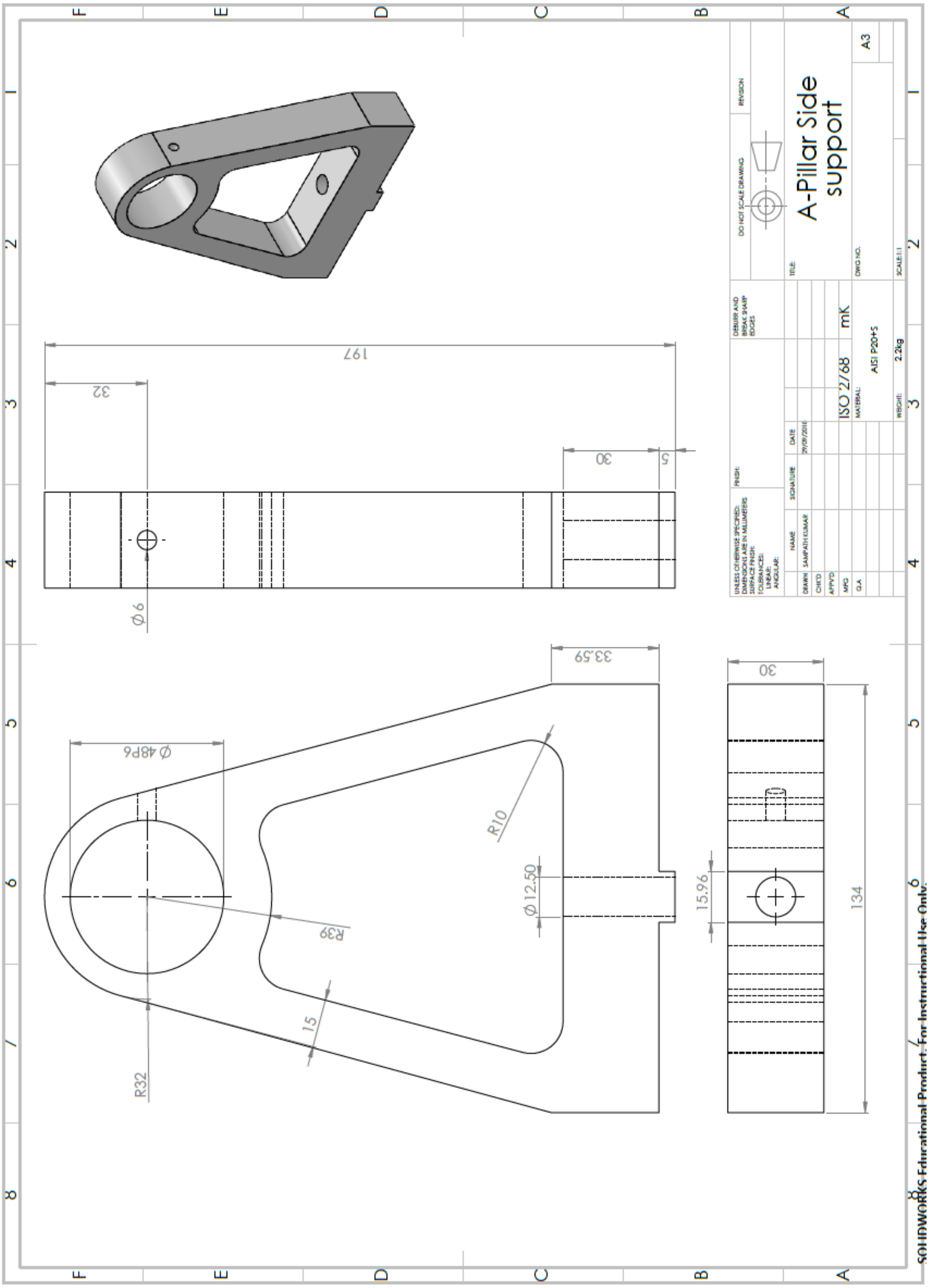
20
SOLIDWORKS Educational Product. For Instructional Use Only.

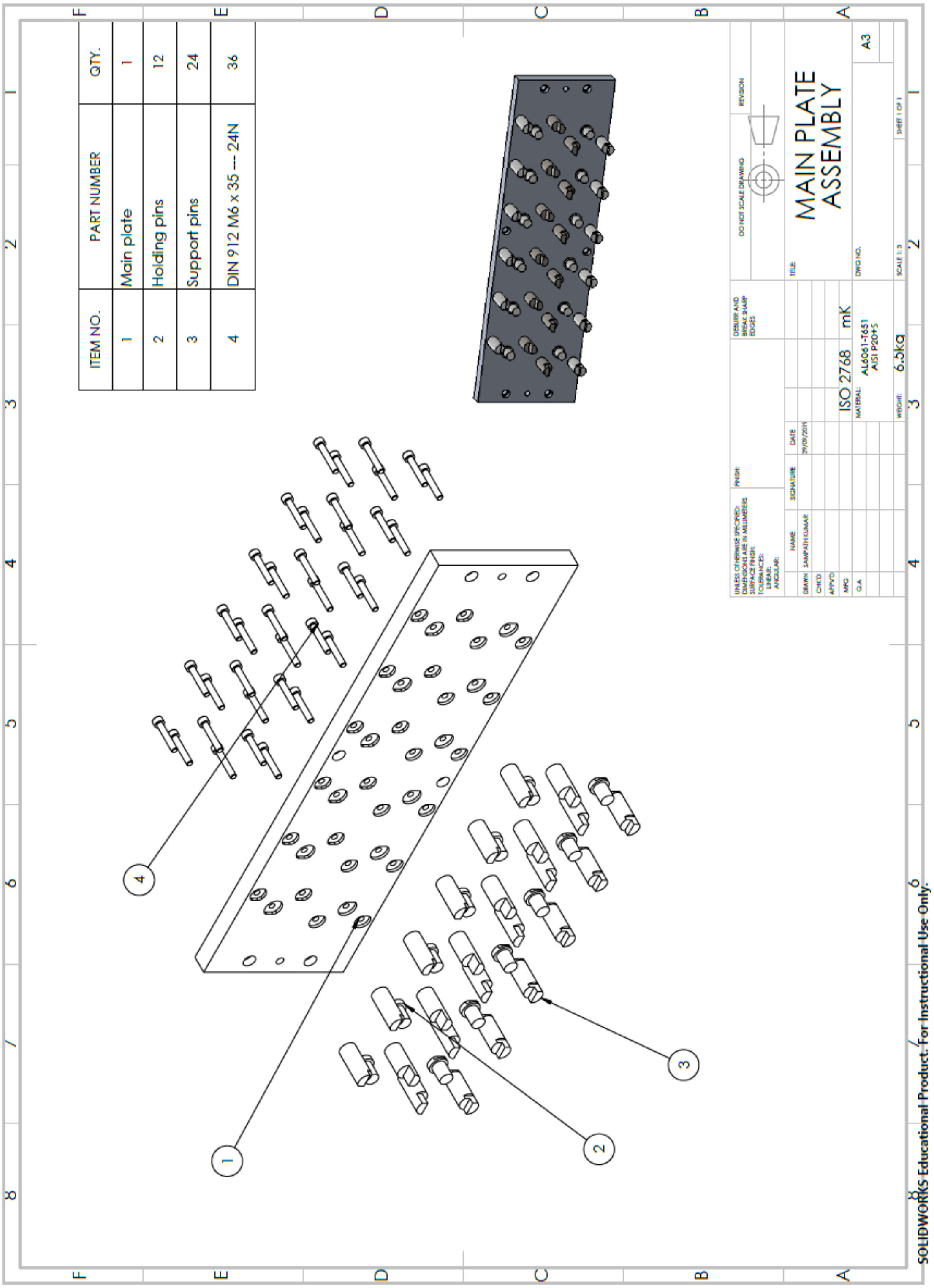

MAIN PLATE
A3
ISO 2768 mK
AL 6061-T651
4.5kg
SOLIDWORKS Educational Product. For Instructional Use Only.

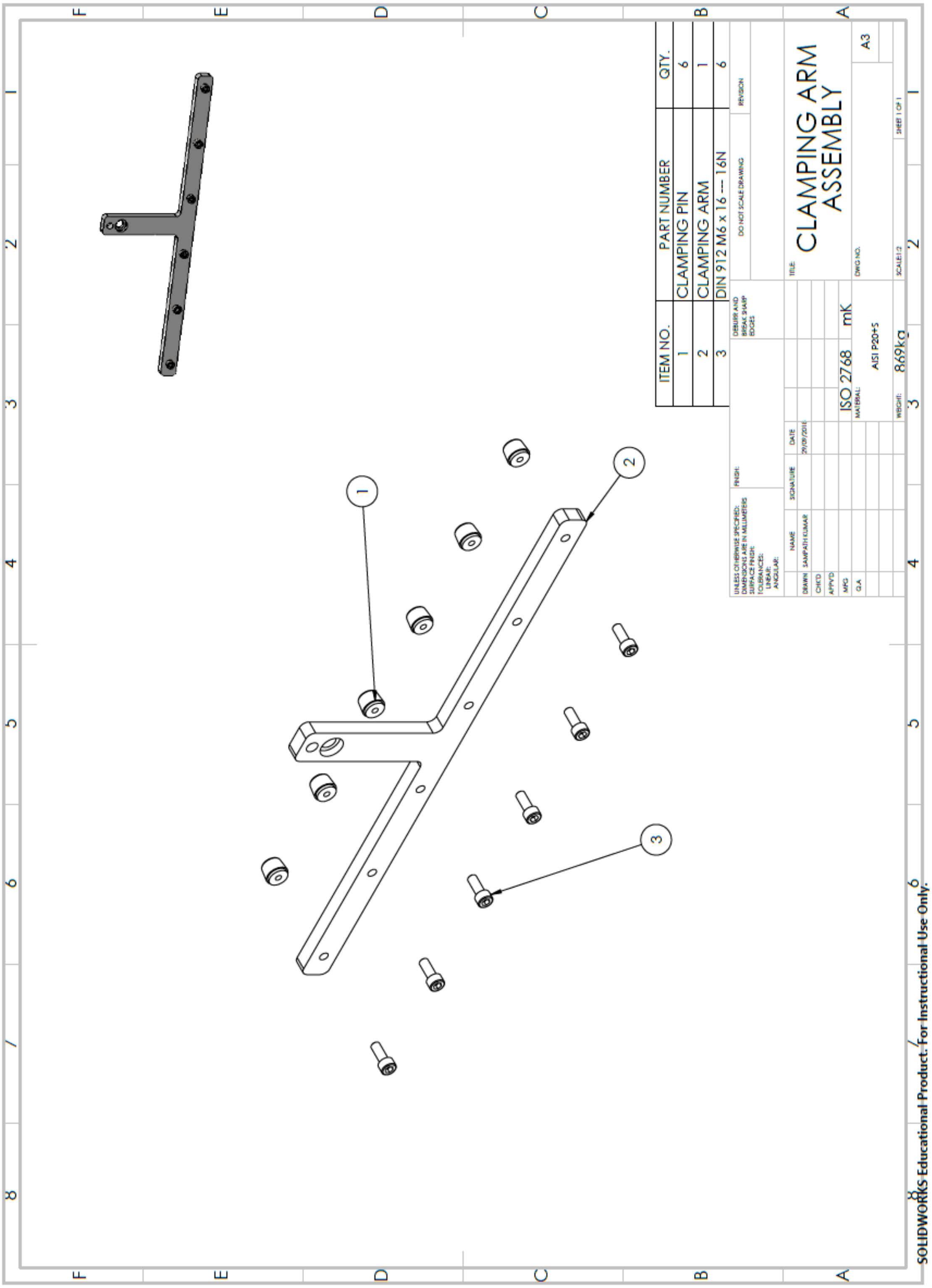

MACHINING MAIN PLATE
ISO 2768 mK
AL 6061-T651
4.5kg
A3
SAMPATH KUMAR
29/9/2018
C (X 190.38, Y83.95)
540
20
(XXX) - in the brackets are the coordinates according to the CNC
SOLIDWORKS Educational Product. For Instructional Use Only.


PNEUMATIC HOLDER
TRUE R10
TRUE R10
ISO 2768 mK
AL 6061-T4(SS)
165g
SAMPATH KUMAR
A3
SOLIDWORKS Educational Product. For Instructional Use Only.


CHUCK SIDE SUPPORT
DO NOT SCALE DRAWING
REVISION
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS
DEBURR AND BREAK SHARP EDGES
DRAWN SAMPATH KUMAR
ISO 2768 mK
MATERIAL: AISI P20+S
WEIGHT: 2.07kg
A3
SCALE:1:1
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.


A-Pillar Side support
A3
AISI P20+S
2.2kg
ISO 2768 mK
SAMPATH KUMAR
29/09/2016
DO NOT SCALE DRAWING
SOLIDWORKS Educational Product. For Instructional Use Only.
197
32
30
5
Ø 6
33.59
Ø 48P6
R10
Ø 12.50
15.96
134
R39
15
R32


ITEM NO.
PART NUMBER
QTY.
1
Main plate
1
2
Holding pins
12
3
Support pins
24
4
DIN 912 M6 x 35 --- 24N
36
MAIN PLATE ASSEMBLY
A3
ISO 2768 mK
AL6061-T651
AISI P20+S
6.5kg
SAMPATH KUMAR
SOLIDWORKS Educational Product. For Instructional Use Only.


ITEM NO.
PART NUMBER
QTY.
1
CLAMPING PIN
6
2
CLAMPING ARM
1
3
DIN 912 M6 x 16 --- 16N
6
CLAMPING ARM ASSEMBLY
ISO 2768 mK
AISI P20+S
8.69kg
SAMPATH KUMAR
A3
SOLIDWORKS Educational Product. For Instructional Use Only.

6.2 ANNEX2

G-codes

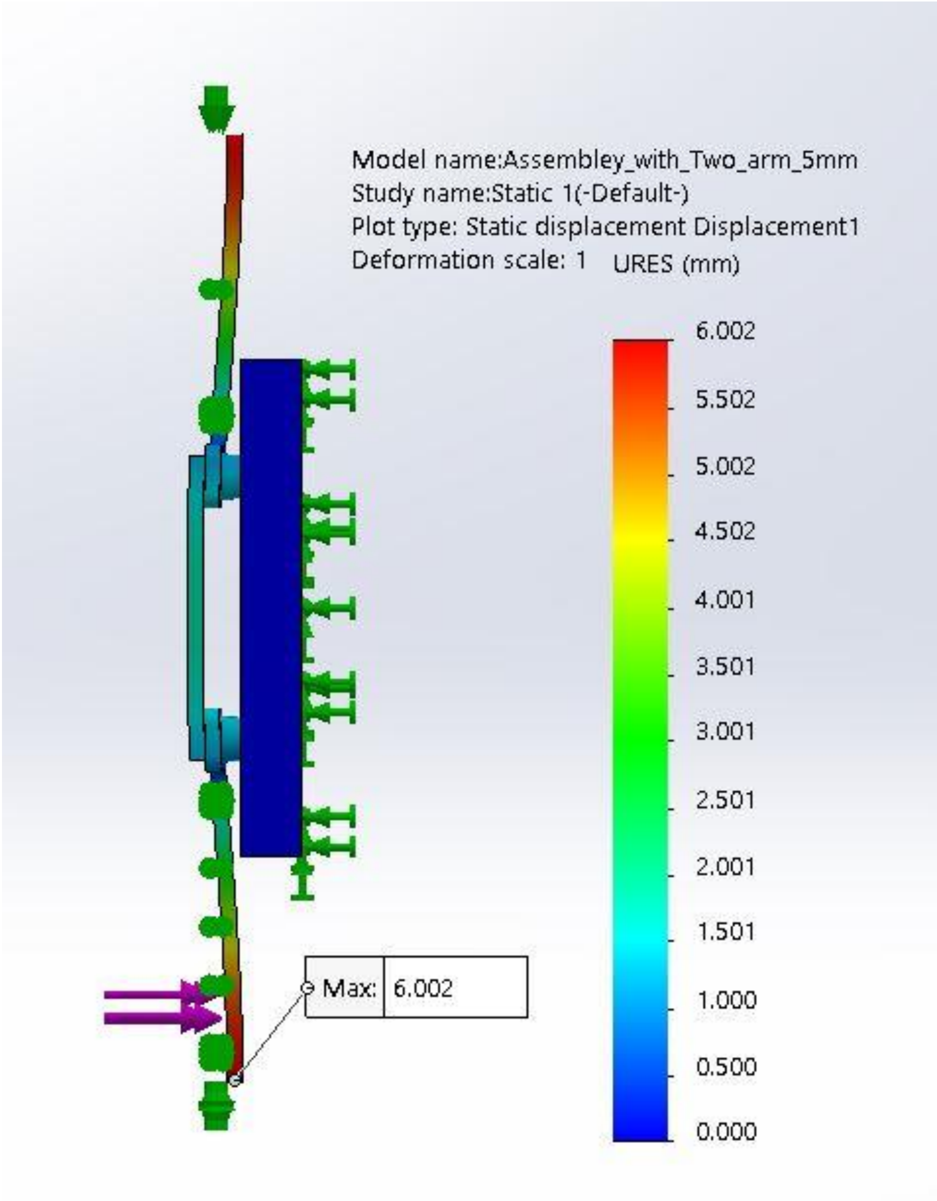
Codes	Description
G00	Rapid Linear Interpolation
G01	Linear Interpolation
G02	Clockwise Circular Interpolation
G03	Counter Clockwise Circular Interpolation
G04	Dwell
G05	High-Speed Machining Mode
G10	Offset Input By Program
G12	Clockwise Circle With Entrance And Exit Arcs
G13	Counter Clockwise Circle With Entrance And Exit Arcs
G17	X-Y Plane Selection
G18	Z-X Plane Selection
G19	Y-Z Plane Selection
G28	Return To Reference Point
G34	Special Fixed Cycle (Bolt Hole Circle)
G35	Special Fixed Cycle (Line At Angle)
G36	Special Fixed Cycle (Arc)
G37	Special Fixed Cycle (Grid)
G40	Tool Radius Compensation Cancel
G41	Tool Radius Compensation Left
G42	Tool Radius Compensation Right

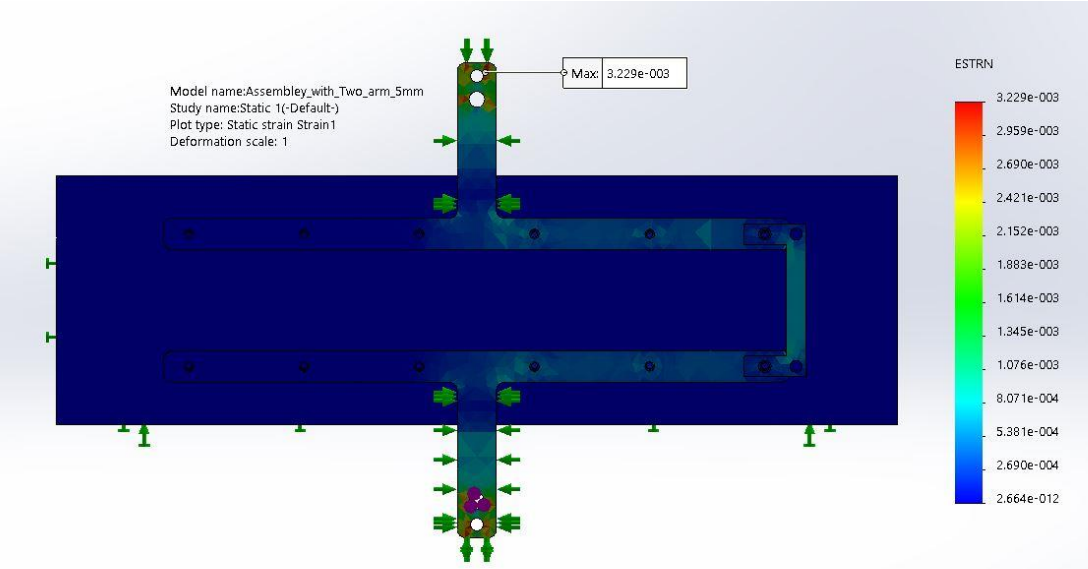
G43	Tool Length Compensation
G44	Tool Length Compensation Cancel
G45	Tool Offset Increase
G46	Tool Offset Decrease
G50.1	Programmed Mirror Image Cancel
G51.1	Programmed Mirror Image On
G52	Local Coordinate Setting
G54 - G59	Work Coordinate Registers 1 Thru 6
G60	Unidirectional Positioning
G61	Exact Stop Check Mode
G65	Macro Call (Non-Modal)
G66	Macro Call (Modal)
G68	Programmed Coordinate Rotation
G69	Coordinate Rotation Cancel
G73	Fixed Cycle (Step)
G74	Fixed Cycle (Reverse Tapping)
G76	Fixed Cycle (Fine Boring)
G80	Fixed Cycle Cancel
G81	Fixed Cycle (Drilling / Spot Drilling)
G82	Fixed Cycle (Drilling / Counter Boring)
G83	Fixed Cycle (Deep Hole Drilling)
G84	Fixed Cycle (Tapping)
G85	Fixed Cycle (Boring)

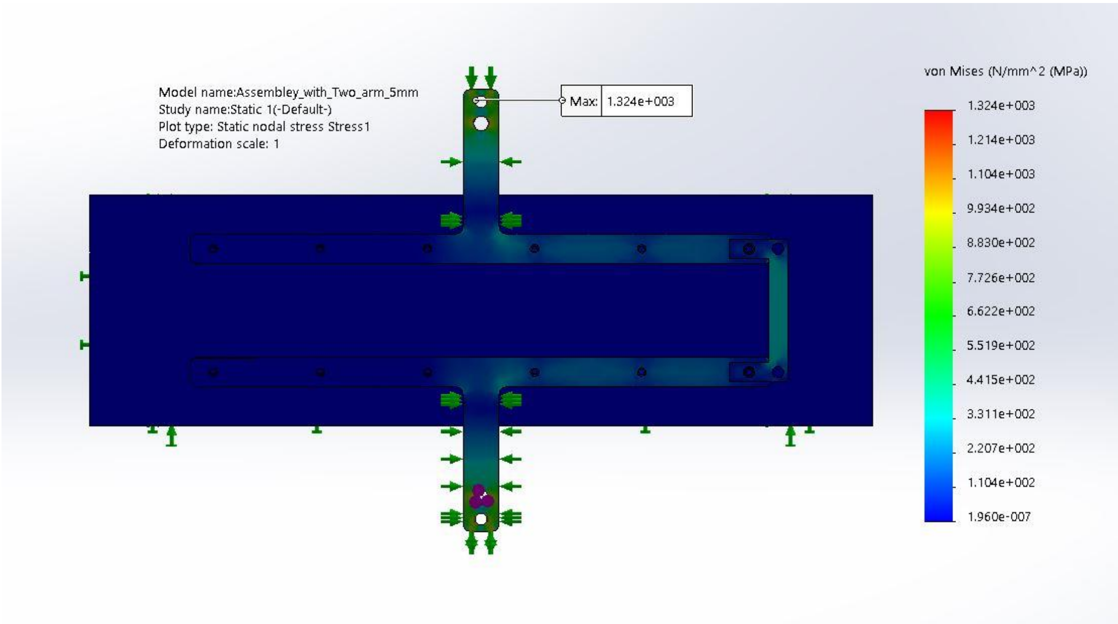
G86	Fixed Cycle (Boring)
G87	Fixed Cycle (Back Boring)
G88	Fixed Cycle (Boring)
G89	Fixed Cycle (Boring)
G90	Absolute Value Command
G91	Incremental Value Command
G92	Work Offset Set
G101	User macro 1 (substitution) =
G102	User macro 1 (addition) +
G103	User macro 1 (subtraction) -
G104	User macro 1 (multiplication) *
G105	User macro 1 (division) /
G106	User macro 1 (square root)
G107	User macro 1 (sine) sin
G108	User macro 1 (cosine) cos
G109	User macro 1 (arc tangent) tan
G110	User macro (square root)
G200	User macro 1 (unconditional branch)
G201	User macro 1 (zero condition branch)
G202	User macro (negative condition branch)

6.3 ANNEX3

FEA results of Table 37 - Simulation variables and results.


Model name:Assembley_with_Two_arm_5mm
Study name:Static 1(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 1
URES (mm)
6.002
5.502
5.002
4.502
4.001
3.501
3.001
2.501
2.001
1.501
1.000
0.500
0.000
Max: 6.002


Model name:Assembley_with_Two_arm_5mm
Study name:Static 1(-Default-)
Plot type: Static strain Strain1
Deformation scale: 1
Max: 3.229e-003
ESTRN
3.229e-003
2.959e-003
2.690e-003
2.421e-003
2.152e-003
1.883e-003
1.614e-003
1.345e-003
1.076e-003
8.071e-004
5.381e-004
2.690e-004
2.664e-012


Model name:Assembley_with_Two_arm_5mm
Study name:Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1
Max: 1.324e+003
von Mises (N/mm^2 (MPa))
1.324e+003
1.214e+003
1.104e+003
9.934e+002
8.830e+002
7.726e+002
6.622e+002
5.519e+002
4.415e+002
3.311e+002
2.207e+002
1.104e+002
1.960e-007

6.4 ANNEX4

Student Intern Performance Evaluation

Term of internship: 12-03-2018 to 28-09-2018
Date of evaluation: 16-10-2018
Student name: Sampath Kumar
Organization name: Fundwell – Fundição Injetada, Lda.
Supervisor: Patrícia Ferreira
Supervisor email/ phone: patricia.ferreira@fundwell.pt / 925009878

Faculty Internship Cordinator: Francisco Silva / fgs@isep.ipp.pt

Skills	1	2	3	4	5
Oral communication					X
Written communication					X
Initiative					X
Interaction with staff				X	
Attitude					X
Dependability				X	
Ability to learn					X
Planning and organization					X
Professionalism					X
Creativity					X
Quality of work					X
Productivity				X	
Appearance					X
Adaptability to organization's culture and policies				X	
Overall performance					X

1 – Unsatisfactory | 2 – Fair | 3 – Satisfactory | 4 – Good | 5 – Excellent

Job Description
Knowledge of organization Perception of the different internal processes Identification of improvement opportunities Study of the specific process and development of tools in order to optimize the processes Implementation of lean methodologies. Evaluation of the effectiveness of the implemented actions.

Observations
Since of the first contact with Sampath Kumar we understand that he will be a great intern. In the first interview, where I was present, Sam soon demonstrated a person with a lot of desire to learn and without any problem of working on the productive part of the project. During the development of the project, we realize that Sampath has a wide range of valences valued in the business world. He showed to be a modest person, endowed with a brilliant intelligence and always with different new proposals to optimize not only the process he was working but also other processes with which he had contact. He was always available to perform all kinds of tasks that he was asked to do, and he put in it every effort he could, achieving always a brilliant result in all that was proposed to him. We are very proud of the evolution Sampath showed since the beginning of the project to its completion. We truly recommend Sampath for all functions associated with industrial and mechanical engineering. We are certain that Sampath will perform well on any project that is proposed to him.

Patrícia Ferreira
(Organization Supervisor)

FUNDWELL - Fundição Injectada, Lda.
Rua da Ribeira
4470 Gueifães
Contribuinte N.º 506 755 371

16-10-2018