Manufacturing Methods of Foam for U-Value Meters

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Abstract:

The thesis is dependent upon a manufacturing conundrum of finding the best method of manufacturing for medium run productions. In this case 100 units of foam insulation for the U-Value Meters. These U-Value Meters have been developed at Arcada since 2010 in order to determine how well a wall thermally insulates. This numerical analysis of thermal resistance is known as a U-Value, hence the name U-Value Meter. The meter has been extremely successful both locally and abroad, consequently more metres were required. The construction of the meter revolves around a foam core that holds all the components in place whilst simultaneously thermally insulates those components allowing a measurement to be taken. The aim was therefore “to select a mass manufacturing means for the U-Value Meter’s internal foam with a primary focus on cost and time for 100 units”. Although cost and time were the key criteria, each method was analysed via a SWOT Analysis, an analytical tool for the methods’ Strengths, Weaknesses, Opportunities and Threats, hence “SWOT”. The three manufacturing methods of Milling, Do It Yourself (DIY) and steam Expanded Polystyrene (EPS) were analysed and compared. It was found that for a quantity of 100 no method was outstanding, yet both milling and DIY were appropriate, especially considering the units were made entirely in house at Arcada. Having said that, in the future if more than 200 units are required the best manufacturing method when considering time and money is via steam-expanded polystyrene.

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Glossary of Terms

Polymers

Ps	Polystyrene
EPS	Expanded Polystyrene
Pu	Polyurethane
PLA	Polylactic Acid

Temperature and Energy

K	Kelvin
C	Celcius
W	Watt
k	Thermal Conduction Coefficient (W/m°C)
h	Heat Transfer Coefficient (W/m°C)

Printing

FDM	Fused Deposition Modelling
SLA	Stereolithography
UV	Ultra Violet

U-Value Meter

AUX	Auxiliary
PCB	Printed Circuit Board

Moulding

Flash	Excess material forced through the part line
Part line	Divider between the mould halves

Units

g	Gram
kg	Kilogram (10^3 Grams)
N	Newtons ($kg.m.s^{-2}$)
m	Metre
mm	Millimetre (10^{-3} Metres)
L	litres (10^6 mm^3)
Bar	100 kPa
Pa	Pascal ($1\ N/m^2$)

Milling

RPM	Revolutions per minute (of the cutting tool)
Cutting Speed	The speed difference between the cutting tool and the work surface in mm/min
d	Diameter of the cutting tool in mm
Feed rate	The velocity that the cutting surface advances into the material
Chip load	The radial depth of a tooth per single revolution
No. of teeth	The number of cutting surfaces on the tool
G-Code	Instructions for the machine in CNC
CNC	Computer Numerical Control

1. Introduction

1.1 Aim

To select a mass manufacturing means for the U-Value Meter's internal foam with a primary focus on cost and time for 100 units.

1.2 Research Question and Hypothesis

What is the most appropriate manufacturing method for the U-Value Meters' internal foam for a quantity of 100?

It is expected to find an appropriate manufacturing method, however as the desired quantity is between short and long run, an optimal method is not expected.

1.3 Objective and Structure

In order to fulfil stated aim, it will be necessary to understand the required needs before researching foam classifications and materials. Consequently, this will be followed by an analysis of manufacturing methods for appropriate foams and an examination of how the item in question is currently produced via milling. Other methods of DIY and EPS will then be examined. The results will then be analysed, compared and discussed with a focus on time and cost in connection with a SWOT analysis.

1.4 What is a U-Value Meter?

Since 2010 Arcada University of Applied Science has developed the U-Value Meter. In short, the device is used in order to define energy loss in the form of heat through varying surfaces. See figure 1. below. The mathematics of heat transfer and the application of the meter is examined on the following pages.

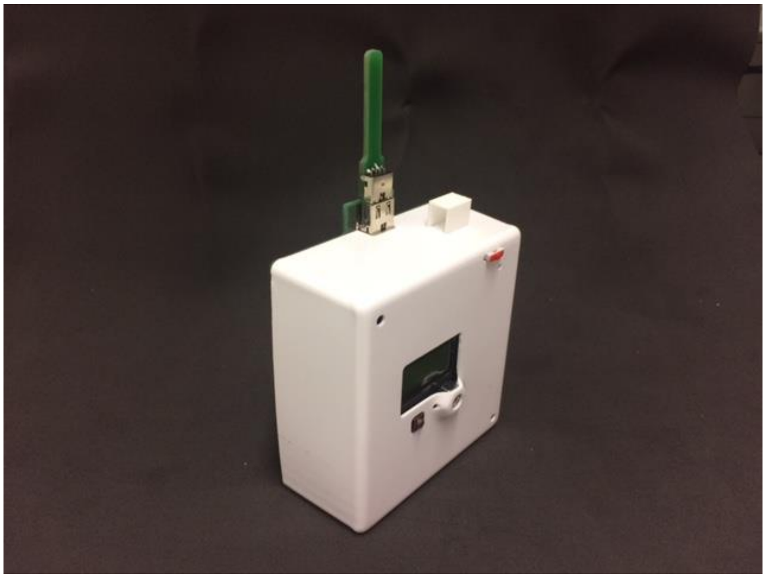


Figure 1. U-Value Meter

2. Theory

2.1 Heat Transfer

Heat transfer is categorized via convection, conduction and radiation. Convection refers to fluid movement due to heat energy where the "molecules expand upon introduction of thermal energy. As temperature of the given fluid mass increases, the volume of the fluid must increase by the same factor" (Cengel, 2012) this in turn causes fluid and energy displacement. Conduction "transfers heat via direct molecular collision" (Gonzalez, 2015) such that the higher speed (energy) particles will collide with those of lower kinetic energy consequently speeding them up and increasing their kinetic energy. Radiation "generates from the emission of electromagnetic waves. These waves carry the energy away from the emitting object" (Gonzalez, 2015). However, in regards to the U-Value Meter, only conduction is measured and relevant as explored in the following sections.

2.2 Theoretical Conduction

Mathematically thermal resistance is calculated by adding the thermal conduction of the elements of the wall in series. One such example is as follows:

"Consider a 1.2 m high and 2 m wide glass window whose thickness is 6 mm and thermal conductivity k = 0.78 W/m°C. Determine the steady rate of heat transfer through this glass window for a day during which the room is maintained at 24°C while the temperature of the outdoors is -5°C. Take the convection heat transfer coefficients on the inner and outer surfaces of the window to be h_1 = 10 W/m^2°C and h_2 = 25W/m^2°C, and disregard any heat transfer by radiation". (Cengel, 2012, p. 188)

The thermal resistance of a wall is examined in respect to electrical resisters. The rate of heat transfer is considered in series as demonstrated by figure 2. with heat transfer from left to right:

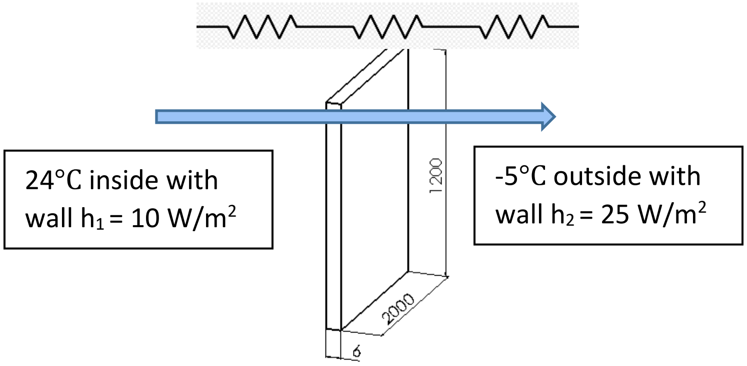


Figure 2. Theoretical Heat Flow

The area (A) = 1,2 X 2 m

= 2,4 m^2

Where: $R = \frac{1}{hA}$ *Equation 1*

$R_{cond} = \frac{l}{KA}$ *Equation 2*

$q = \frac{T_{\infty 1} - T_{\infty 2}}{R_{Total}}$ *Equation 3*

$q = UA\Delta T$ *Equation 4*

$R_{Total} = \frac{1}{UA}$ *Equation 5*

$U = \frac{1}{RA}$ *Equation 6*

(Incropera, 2006, pp. 98-99)

Therefore: $R_1 = \frac{1}{h_1 A} = \frac{1}{10 \times 2{,}4} = 0{,}0416\ {}^{\circ}\mathrm{C}/_{W}$ (see equation 1)

$R_{glass} = \frac{l}{KA} = \frac{0{,}006}{0{,}76 \times 2{,}4} = 0{,}0033\ {}^{\circ}\mathrm{C}/_{W}$ (see equation 2)

$R_2 = \frac{1}{h_1 A} = \frac{1}{25 \times 2{,}4} = 0{,}016\ {}^{\circ}\mathrm{C}/_{W}$ (see equation 1)

Consequently: $R_{Total} = R_1 + R_{glass} + R_2$

$$R_{Total} = 0{,}0616\, {}^{\circ}\mathrm{C}/_{W}$$

Steady Heat Transfer:

$$q = \frac{T_{\infty 1} - T_{\infty 2}}{R_{Total}} = \frac{24+5}{0{,}0616} = 471\, W$$ (see equation 3)

As: $q = UA\Delta T$ and $R_{Total} = \frac{1}{UA}$ (see equation 4,5)

Then: $U = \frac{1}{RA}$ (see equation 6)

$U = \frac{1}{0{,}0616 \times 2{,}4}$ = 6,76 W/m^{2}K

(Incropera, 2006, pp. 98-99)

However, this was just a theoretical example and usually the R$_1$, or RSI (Resistance Surface Internal) is 0,13 and the R$_2$, or RSE (Resistance Surface External) is 0,04.

Given these more realistic values the resistance is therefore:

$$R_{Total} = R_1 + R_{glass} + R_2$$

$$R_{Total} = 0{,}13 + \frac{0{,}006}{0{,}76} + 0{,}04$$

$$R_{Total} = 0{,}178$$

Therefore, the U-Value is calculated more realistically as:

$U = \frac{1}{R}$ (see equation 6)

$U = \frac{1}{0{,}178}$ = 5,6 W/m^{2}K

2.3 What is a U-Value?

A U-Value refers to "the rate of transfer of heat through a structure divided by the difference in temperature across the structure" (Lymath, 2015). Consequently the lower the U-Value the better the insulator with the units given logically in W/m^{2}K (ie. Watts per Metre Squared Kelvin).

However, Arcada University's meter does not rely on theory but rather the recorded energy a wall absorbs in relation to the change in temperature the wall withstands as outlined by equation 7 below.

$$U - Value = \frac{Power\ (W)}{\Delta Temperature \times Area\ (m^2)} = \mathrm{W/m^2K}$$

$$U - Value = \frac{Power\ (mW)}{T_{\infty 2} - T_1} \times \frac{1}{1000 \times 0{,}01\ m^2}$$

(note: the area of the meter is 100 x 100 mm = 0,01m^2)

$$U - Value = \frac{Power\ (mW)/_{10}}{T_{\infty 2} - T_1} \qquad \textit{Equation 7}$$

For example if the meter shows a temperature of 20 degrees Celsius and power of 140 mW when the outside temperature is 7 degrees, the U-Value is calculated as follows:

$$U - Value = \frac{140/_{10}}{20-7} = 1{,}08\ \mathrm{W/m^2K}$$

2.4 Practice

Materials should hold stable insulation properties irrelevant of the application however, "workmanship and installation standards can strongly affect the thermal transmittance. If insulation is fitted poorly, with gaps and cold bridges, then the thermal transmittance can be considerably higher than desired". (Lymath, 2015). This results in buildings requiring greater heating than initially calculated costing more in the end and preventing classifications of "passive houses". A passive house is a "building standard that is truly energy efficient, comfortable and affordable at the same time" (About Passive House - What is a Passive House?, 2015). They usually make use of the surrounding nature such as the sun or internal heat sources so that the energy demand does not exceed 15 kWh/m^2 (About Passive House - What is a Passive House?, 2015).

2.5 Applications

By giving true insulation data on specific walls, appropriate measures can be taken to improve the structure. For example if it is discovered that a building is losing extensive energy through the windows, then adding double glazed may significantly decrease the heating cost and pay off the new windows within a 10 -12 years for example.

The applications include not only improving pre-existing structures as examined above, but also in recommendations for improving building standards, cost optimization of new structures and recommendations for heritage listed buildings.

2.6 The Competition

There are pre-existing heat flux meters that use a thermopile sensor attached to a surface that calculate the thermal transmittance by dividing the heat flow by the average temperature difference over a period of weeks (Lymath, 2015). This method has huge disadvantages due to the timeframe, cumbersome equipment and disturbance to the inhabitance. The Meter developed at Arcada is small and light leaving no residue as well as producing reliable measurements within an hour or two without the need for cables.

2.7 The Construction of the Meter

The meter is constructed in a sandwich format of a lower circuit board followed by an insulating foam topped with a top circuit board nestled within the protective case. Note that the case does not cover the active base circuit board that supplies the energy to the contact surface. See figure 3. Below.

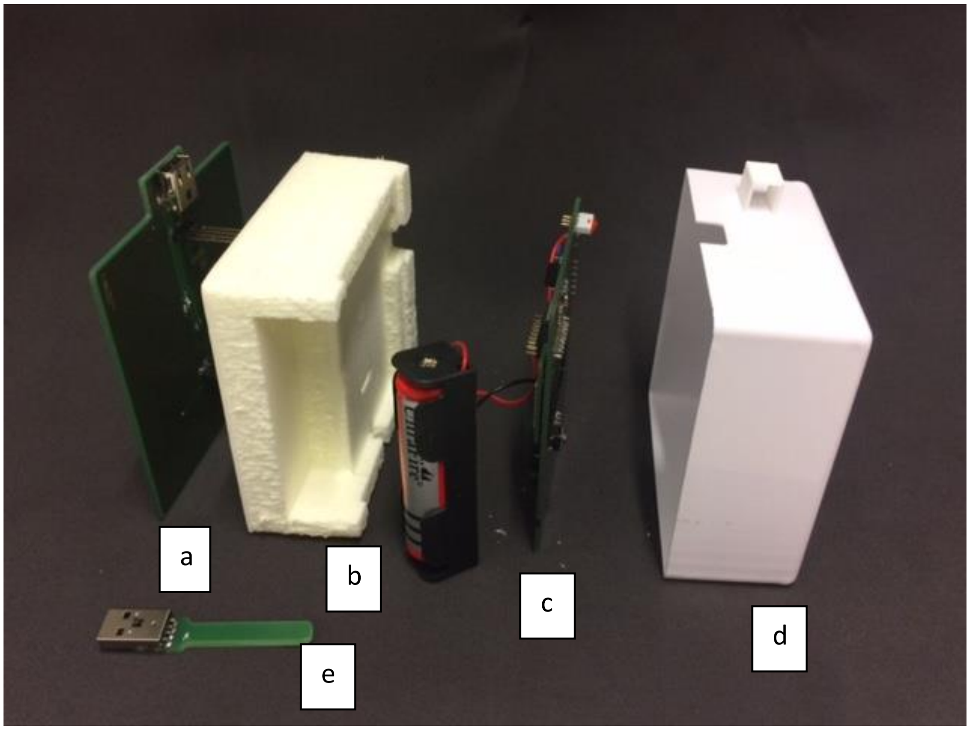


Figure 3. Exploded U-Value Meter

a. The base circuit board contains a heating element with thermometer located in the middle. Wires extend off the plate to connect with the top circuit board. A female USB connection attaches the reference pin at the top.
b. The foam thermally isolates the boards and offers rigidity to the structure. See the following page.
c. The top circuit board contains the electronics, screen, switches, battery connection, LCD display and a facing down female AUX connection for data transfer and charging.
d. The external reference pin contains a thermometer connected to the base board via a male USB connector. It is housed in the case under the top bridge when not in use.
e. The case protects the unit, houses a ¼”- 20 photography nut for measurements taken on difficult surfaces and a magnet to hold the reference pin on the top.

Note; there are plastic nut towers and screws holding all pieces together left out of the figure.

2.8 Need for the Internal Foam

The foam has two key roles, to isolate thermally the electronics so any heat generated by the battery does not reach the base circuit board. In addition, the foam holds the device together in one piece making a robust package. This in turn allows for measurements to be taken.

2.9 Types of Manufacturing

There are two key forms of manufacturing, additive and subtractive. Subtractive manufacturing is considered traditional manufacturing as it relies on removing material from a larger block. This means of production is often achieved via milling or turning (Paramasivan, 2016). Additive manufacturing relies on "successively depositing material in layers such that it becomes a predesigned shape" (Paramasivan, 2016). The most common form of additive manufacturing is 3D printing that rely on slicing a design into layers that are then created one at a time. See section 2.14.1 for more information on SLA printing.

2.10 Short vs. Long Run Strategy

Production can also be considered in two other lights, short and long run (Investopedia). Companies especially refer to strategy as either short or long run. In essence, short run refers to the company's ability to fulfil the current agreements and contracts without the need for expansion. When considering the U-Value Meters, all that was actually needed at the beginning of this thesis was 20-30 metres for the current orders. This is short run. Whereas the long run refers to the ability to fulfil hypothetical or desirable contracts. In this situation all factors (such as size of the operation, duration of the lease and desired output) are in flux, ie. can be changed (Investopedia). In regards to quantity of the metres long run refers to 500 or more units. Consequently, the U-Value metre project is in a state of short run, with a plan of long run yet with a desired quantity of metres in between. Unfortunately manufacturing methods are only financially viable as short or long run, but not in between. This is the conundrum of medium run production.

2.11 Computer Aided Design

CAD or ‘Computer Aided Design’ refers to a plethora of computer-based programs that facilitate the creation of two or three-dimensional graphical representations of physical objects (Siemens, CAD/ Computer- Aided Design, 2017). The reasons for using this software include:

- Superior and more accurate visualisation of the final product including assemblies and interlocking parts.
- Improved accuracy compared to manual techniques.
- Better documentation of designs.
- The ability to reuse design data easily.

(Siemens, CAD/ Computer- Aided Design, 2017)

Some of the most common computer programs include:

- AutoCAD
- Rhinoceros 3D
- Solid Edge
- SolidWorks

2.12 Computer Aided Manufacturing

Computer aided manufacturing or CAM “refers to the use of numerical control (NC) computer software applications to create detailed instructions (G-code)” (Siemens, CAM / Computer-Aided Manufacturing, 2017) these instructions instruct computer numerical controlled (CNC) tools to manufacture the part. (Siemens, CAM / Computer-Aided Manufacturing, 2017). The benefits of using CAM include:

- Maximising the full potential of production tools such as speeds and feeds and also part complexity.
- Standardise production with product lifecycle management
- Aid in producing shop documentation

Examples of CAM software include:

- Mastercam
- SolidCAM

2.13 Milling Theory

Milling is subtractive manufacturing as outlined in section 2,9 above and relies on some simple equations to ensure safe and optimal cutting. Milling uses spinning bits with cutting teeth that move in the x, y, z planes in order to remove material from a block. Consequently, there are restrictions placed by the material being removed and the cutting tool. One such example is if the tool removes too much material at a time the tool can become stuck or break however if too little is removed per cut then the tool needs to make more cuts for the same outcome wearing out the tool and taking unnecessarily long. Therefore, speeds and feeds are calculated in respect to the material being cut. The general rule is the harder the material, the slower the cut.

Therefore,

$$RPM = \frac{(Cutting\ Speed)}{\pi d}$$

Equation 8

$$\text{Feed Rate} = RPM \times \left(\frac{Chip\ load}{tooth}\right) \times No.Teeth$$

Equation 9

(Smid, 2003, p. 524)

Where,

- Cutting speed is the speed difference between the cutting tool and the work surface in mm/min
- d is diameter of the cutting tool in mm
- RPM is the revolutions per minute (of the cutting tool)
- Feed rate is the velocity that the cutting surface advances into the material
- Chip load is the radial depth of a tooth per single revolution
- No. of teeth is the number of cutting surfaces on the tool

(Smid, 2003, p. 524)

2.14 Supportive Manufacturing Theory

2.14.1 SLA Printing

SLA or Stereolithography is a form of additive manufacturing used in section 3.2.6 of this thesis. The part is constructed layer by layer by a UV laser (or projector) curing a UV sensitive liquid resin. The production means is sensitive to overhangs however supports can be generated and are easily removed as the cured resin is often brittle (Materialise). See figure 4. below.

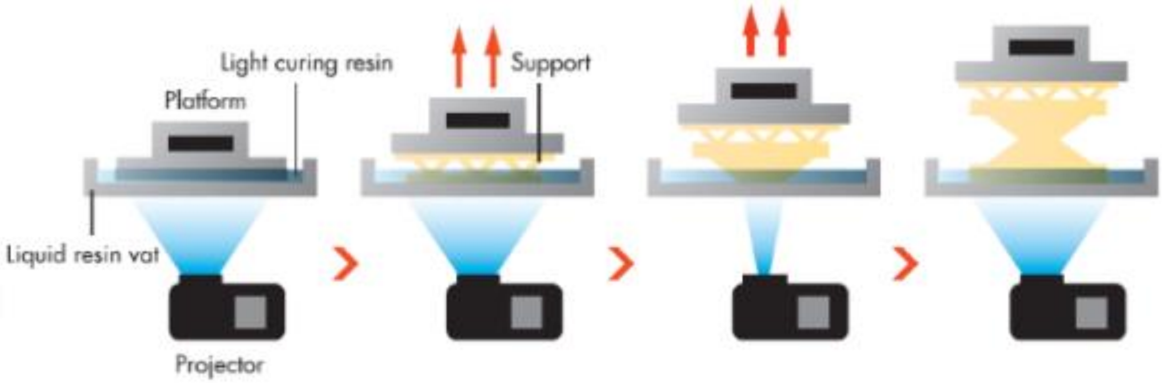


Figure 4. SLA Printing, courtesy of (Hipolite, 2014)

2.14.2 Silicone

Casting silicone is used in section 3.2 and is utilised for the DIY method of foam production. Silicone is an inorganic polymer as it is constructed of chains of alternating silicon and oxygen atoms, differing from the conventional carbon chains of organic polymers (Britannica, 2009). Having said that usually vinyls (CH_2), methyls (CH_3) or phenyls (C_6H_5) are attached to the silicone atom chains as silicone is tetravalent (bonds on four electrons) (Britannica, 2009). Therefore the general formula for silicone polymers is $(R_2SiO)_x$ where R can be any organic group (Britannica, 2009). There are two types of vulcanised silicone rubber depending if they are vulcanised at room temperature (RTV) or at high temperatures (HTV). Usually RTV silicones are of lower molecular weight (Britannica, 2009). Having said that the general properties of silicones are: resistant to heat and cold, flexible, water repellent and easily sterilised (Wacker, 2017). These properties make them appropriate for protecting electronics, sealing bathrooms, casting moulds and medical uses such as wound dressings (Wacker, 2017).

2.15 History of Polymer Foams

Polymer foams have been developed since the 1920s starting with that of latex foams (Frisch, 2006). In regards to latex foams, two key production methods of the timeframe are most relevant known as the Dunlop and Talalay processes. Both processes rely on vulcanization (liquid latex expanded and hardened by use of cross-linking with sulphur) of the rubber to expand into the mould. However, the Talalay process uses a vacuum to expand the foam followed by freezing and the addition of carbon dioxide prior to vulcanization (Anonymous, 2017).

These innovations encouraged the development of flexible, semi flexible and rigid foams in use today. Within the flexible classification, materials commonly used include polyvinyl chloride, polyolefin, urethane, silicone and fluorocarbons (Frisch, 2006). In regards to rigid foams, the most common materials include polystyrene, polyurethane and those of an epoxy base (Frisch, 2006).

2.16 Foam Cell

As foam cavities are constructed from bubbles, there are two key structures, open and closed (Kevin, 2016). Open refers to cavities that are connected and able to 'breath', closed refers to those cavities that a completely separated by the foam. Please see figure 5. below.

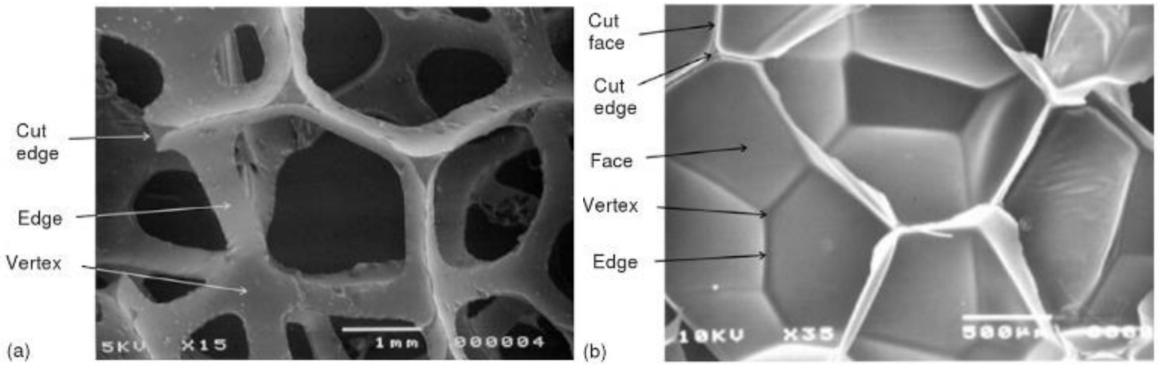


Figure 5. Open (a.) Vs Closed (b.) Cell Foam, Courtesy of (Mills, 2007, p. 2)

2.17 Foam Density

Foam density is analysed proportionally to the density of the raw material. Of course the foam material has exactly the same weight per volume, however when the cavity volume increases, then the density decreases (Mills, 2007, p. 3). Consequently, the equation is as follows:

$$R = \frac{\rho_f}{\rho_P} \qquad \textit{Equation 10}$$

Where the R is the relative density, ρ_f is the foam density and ρ_P is the material density. “When no other phases (such as glass fibres or solid fire retardant additives) are present, R is the volume fraction of polymer in the foam” (Mills, 2007, p. 3). In these situations it is expected that low density foams have an R less than 0,1.

2.18 Materials of Foams

2.18.1 Polyurethane

The foam expands and crosslinks via the following general polyurethane equation (Udumbasseri, 2016).

$$RN = C = O + HO - R^1 \rightarrow RNH - (OR^1)C = O$$

However, the slabstock foam uses five key materials of:

- Polyol, usually triols making up the bulk of the foam.
- Isocyanate, such as toluene di iso-cyanate is used as a raw material.
- Blowing Agent, usually carbon dioxide used for expansion. It is formed by the reaction of iso-cyanate and water.
- Tin and Amine Catalyst, used to restrict the rate of carbon dioxide formation such as di-methyl amino ethanol or triethylene diamine.
- Silicone Oil Surfactant, to assist uniform mixing preventing collapsed cells.
- The Process may also utalise pigments and fire retardants.

(Udumbasseri, 2016)

2.18.2 Polystyrene

The other key material for foam production is polystyrene. Expanded PS “is manufactured as beads containing pentane. When they are heated in steam, the hydrocarbon volatilises and the bead expands. These are subsequently blown into moulds and fused by further steaming and then cooling” (York, 2014).

2.19 Manufacturing Methods

There are two key manufacturing methods of polymer foams known as slabstock and moulding.

2.19.1 Slabstock

Slabstock refers to a manufacturing technique whereby the foam is continuously deposited and expanded onto a conveyer belt consequently creating a large block or "slab" that is then cut to size. (Academlib, 6.1.1 Slabstock Foams). See figure 6. below.

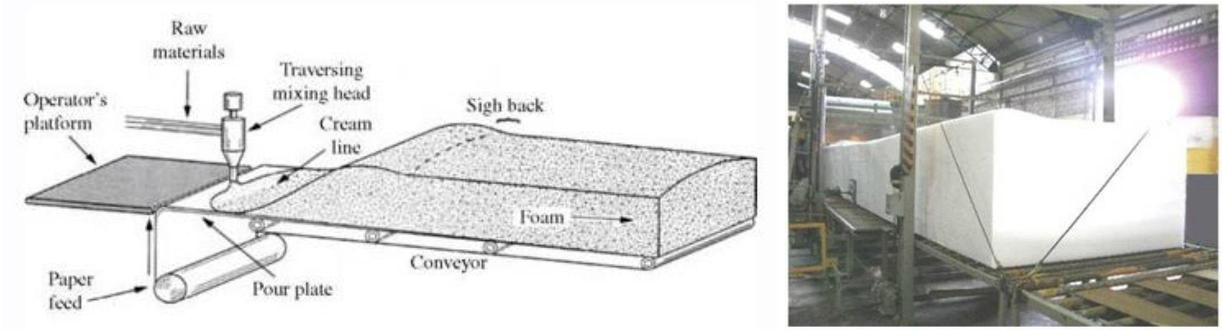


Figure 6. Production of Slabstock Foams, Courtesy of (Academlib, 6.1.1 Slabstock Foams)

2.19.3 Moulding

The second key manufacturing method of polymer foams is moulding whereby "the components of the foam are mixed and injected or poured into a premade mould that the foam fills as it forms. The foam has a set resistance time and is removed" (Academlib, 6.1.2 Molded Foams). See figure 7.

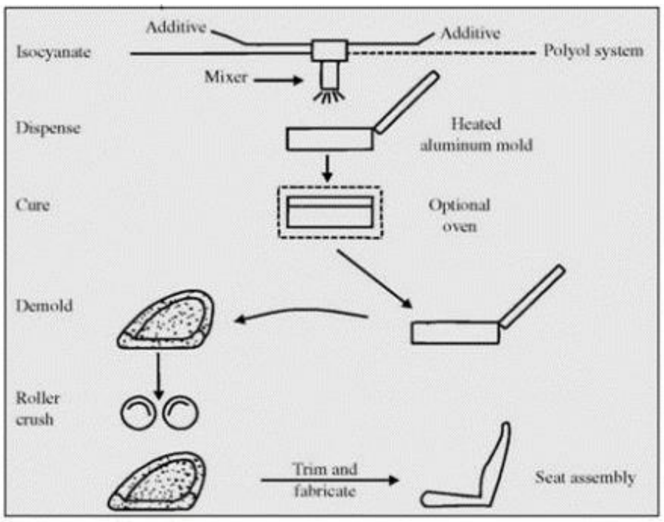


Figure 7. Moulded Foam Production, courtesy of (Academlib, 6.1.2 Molded Foams)

The process of producing expanded polystyrene (EPS) is in three stages. The first stage is pre-expansion where polystyrene beads come into contact with steam and the pre-foaming agent (often pentane) starts to boil causing the beads to expand 40 to 50 times in volume (EPS, 2014). The beads are then conditioned where they are left to mature and reach equilibrium temperature and pressure. The final stage is the placement of the beads in a mould and steam being added once more. This causes further expansion and fusing of the beads to one another (EPS, 2014).

Moulding of foams can be speedup via injection moulding whereby the materials are fed into a screw prior to being pushed into a mould as demonstrated in figure 8.

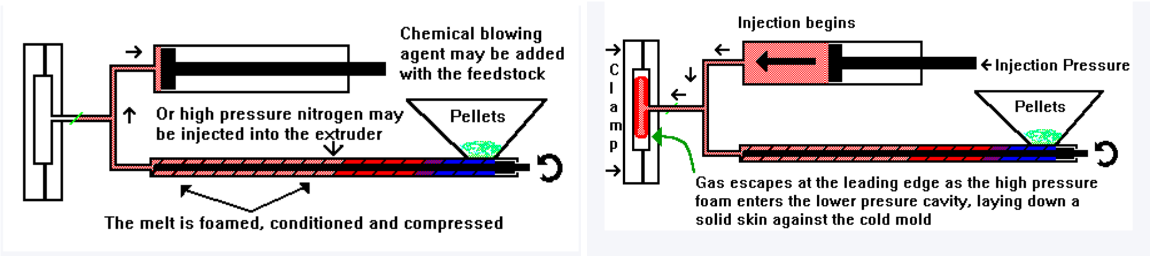


Figure 8. Foam Injection Moulding Process, Courtesy of (Cad)

The advantage of this manufacturing means include:

- Complex designs
- Conditioned during production to ensure closed cell, self-skinned and crosslinked
- Rigid
- Impact resistant
- Relatively fast production per unit
- Cheap moulding as usually only aluminium moulds are required.

(Cad)

2.20 Applications of Foams

The applications of polymer foams are divided into the four key categories of packaging, building and construction, furniture and bedding and automotive (Markets, 2016). The reasons for their applications are logically directly dependent upon their physical properties of thermal /sound insulation, impact/weight absorbance, relative density and affordability. It is important to note that these properties make rigid foams highly useful in the construction of composite cores. This is due to the importance of composite skins absorbing the compressive and tensile loads whilst the foam only holds the skins apart.

2.21 Foam Selection

There are two key reasons for selecting a closed cell foam for this application. The first of which is in regards to rigidity as “open cell foam is soft – like a cushion” (Foam-Tech, 2008) this is not appropriate for the U-Value Meters as an open cell foam would not support the circuit boards as required. The second is logically in relation to thermal isolation. Close cell foam will hold lower U-Values, ie. be better insulators. This is a requirement, as the foam needs to isolate the heat between the circuit boards and the battery. (Foam-Tech, 2008).

2.22 SWOT Assessment Method

When examining and comparing anything it is important to use a fair framework. One of the most common is the SWOT analysis. The tool was initially developed by Albert S. Humphrey in the 1960s to separate internal and external impacts via a matrix (Tools). SWOT is an acronym standing for Strengths, Weaknesses, Opportunities and Threats. Strengths refers to the positive attributes, weaknesses to the negative and are both internal factors. In regards to external factors lies the opportunities (the places to expand) and threats, the hazards. See table 1.

Table 1. SWOT Analysis Outline

INTERNAL		**External**	
Strengths	Assets	Opportunities	Areas to improve
Weaknesses	Shortcomings	Threats	The competition

3. Method

Three manufacturing methods are explored under section 3.1, 3.2 and 3.3. The three manufacturing methods of Milling, DIY and EPS were chosen as they represent a variety of manufacturing strategies from short run to long run. The methods were also chosen as two out of the three can be used in house at Arcada.

3.1 Milling

Until December 2016 the foam for the meters had been milled individually from both sides, this was highly inefficient and consequently the author designed a piece to be milled from only one side. Having said that, it is commonplace the mill, waterjet cut or any other means of subtractive manufacturing processing. This is due to the soft nature of foam whereby exceptionally high speeds and feeds can be used and the tool wears very slowly. It is therefore an affordable method for processing foams with varying dimensions. However, one downside of such a means is the surface as often with the case at Arcada, the foam became 'fluffy' on the milled sides.

3.1.1 Restrictions

Prior to designing the piece it is necessary to first determine the limitations of the in house HAAS milling machine. Consequently, the following restrictions were noted as follows:

- Max size of the milling area is 600 x 300 mm
- Max size of the vacuum table is 300 x 335 mm

Post analysis of the milling restrictions the physical restrictions were analysed as follows:

- Max 100 x 100 x 40 mm dimensions in X, Y, Z orientation
- Draft from thermoformed case is either 0° on one side and 3° degrees on the remaining three.
- The electronics (especially those prone to heating) require a tight tolerance in cable holes to prevent hot or cold channels.
- The battery needs to be as far from the rear circuit board as possible to minimise heat travel.
- Holes need to be milled through the piece for attachment via screw towers to the case of the device.

3.1.2 Foam Choice

The foam was selected as Finnfoam a polystyrene closed cell foam. It is nonhazardous to health comprising of 96-98% polystyrene and carbon dioxide. The remainder consists of colour agents, stabilizers and cell structure modifiers (Finnfoam). The production method of Finnfoam is extrusion compressed, ie. It is a slab that expands into a max width and height consequently developing a rigid hardened waterproof surface on both the top and bottom of the slab. The cell structure is homogeneous and of course closed with a relative density of 32 kg/m^3 (Finnfoam). See section 3.1.9 for the relative density. The material is highly affordable at €13,90 per sheet of 50 x 600x 2500 mm producing up to 250 pieces per sheet.

3.1.3 Design in SolidWorks

Upon analysis of the restrictions, the piece was designed in solidWorks primarily with extrusions and extrude cut features to yield the piece as follows:

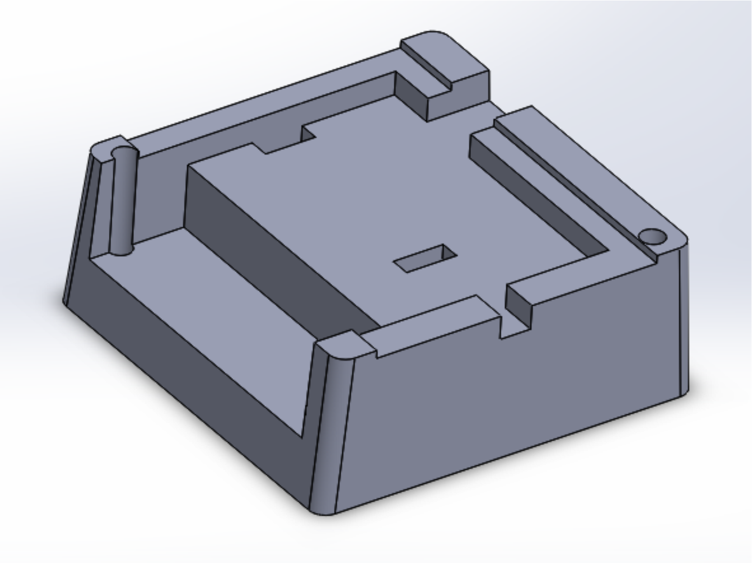
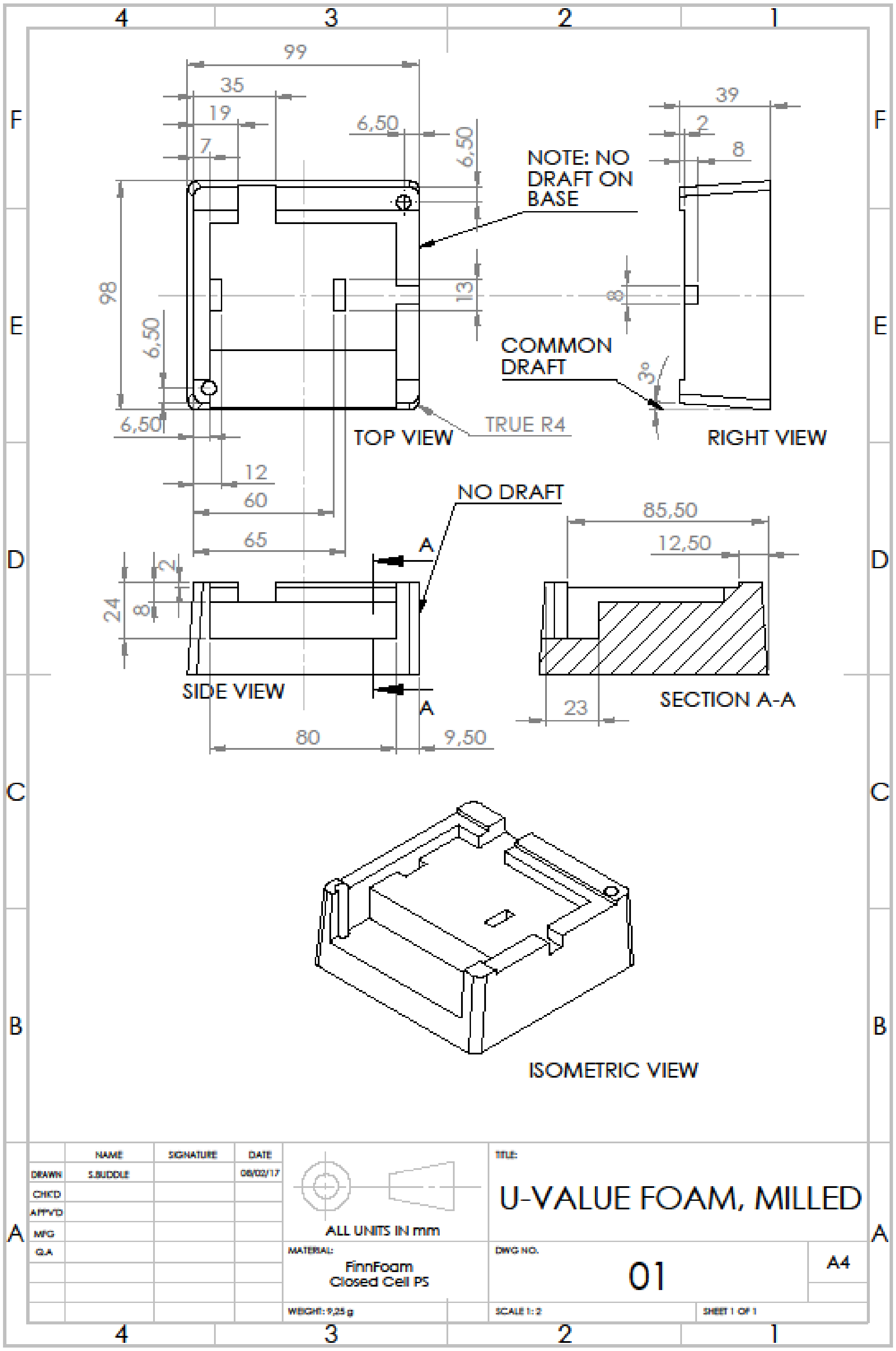


Figure 9. Snipping Tool Image from SolidWorks

Technical drawings of the piece were developed not necessary for milling, but for referencing the produced part. See section 3.1.4.

3.1.4 Technical Drawing of Milled Foam



3.1.5 Design in Mastercam

The design then needs to be analysed and processed in Mastercam in order to produce the G-Code that programs the mill.

In order to attach the foam to the mill one of two options is available, clamping or vacuum. Clamping is very useful as it requires no external vices and can form a strong compression on the work pieces. It is also the easiest to set-up. Using a vacuum table is more time consuming in the setup however it results in a 0,9 bar pressure (90 000 N/m^2) without the need for fixing devices on top of the work piece. It is highly useful for securing foam as it produces a consistent regular force across the base of the piece as opposed to point loads given by clamps. Consequently, a vacuum table is most appropriate. See figure 10.

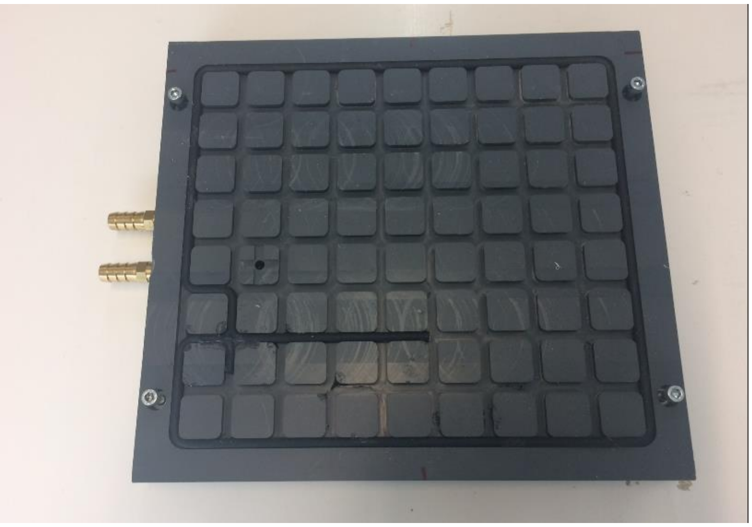


Figure 10. Image of Arcada's Vacuum Table

3.1.6 Production

Erland Nyroth developed the toolpaths and milled four prototypes each with minor changes specified by the student. Erland Nyroth developed a timesaving array of six units per cycle taking 14 minutes per series of six. Upon development of the optimum design the student then developed their own G-code in Mastercam for their own educational purposes as outlined in section 3.1.7.

3.1.7 Milling Procedure

On opening the parasolid file in Mastercam the origin was moved to the top left of the piece as it is the standard location. To achieve this the design was rotated and moved.

The procedure chosen by the student involved nine steps using only three tools to create the shape. Each tool is changed only once to avoid unnecessary tool changes.

Step 1:

Tool: 10 mm end mill

See figure 11. (right)

The tool is HSS or High Speed Steel with 2 teeth that cuts a finishing cutting speed cut of aluminium at 75-105 m/min (Smid, 2003, p. 523). Therefore, as foam is substantially softer than aluminium,

250 m/min is used with a chipload of 0.2 mm/tooth. The revolutions per minute (RPM) feed rate and time is calculated as follows. See equations 8 and 9.

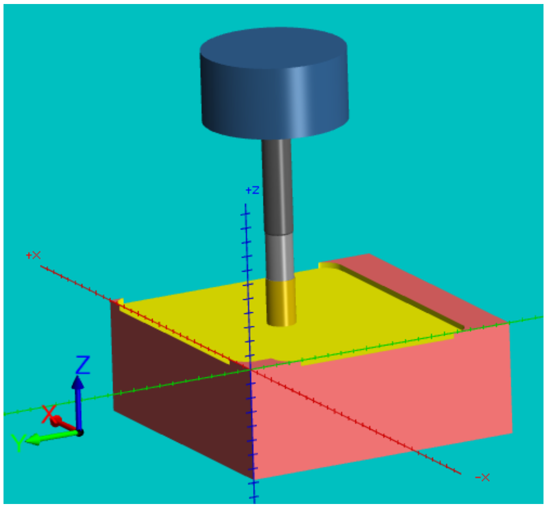


Figure 11. Snipping Tool Image of Step 1 Mastercam Tool Path

RPM = 250 x 1000/(20π)

=3978

Feed rate = 3978 x 0.2 x 2 = 1591 mm/min

Length = 120 mm

Time = 120/1591 = 0,08 minutes

For the following eight operations Mastercam calculated all the speeds and feeds however for the 4 mm end mill the calculations are completely incorrect as it was chosen to use the five times gearbox that runs at 20 000 RPM and therefore the chipload is one fifth if the same speed is used. See figures 12, 13, 14.

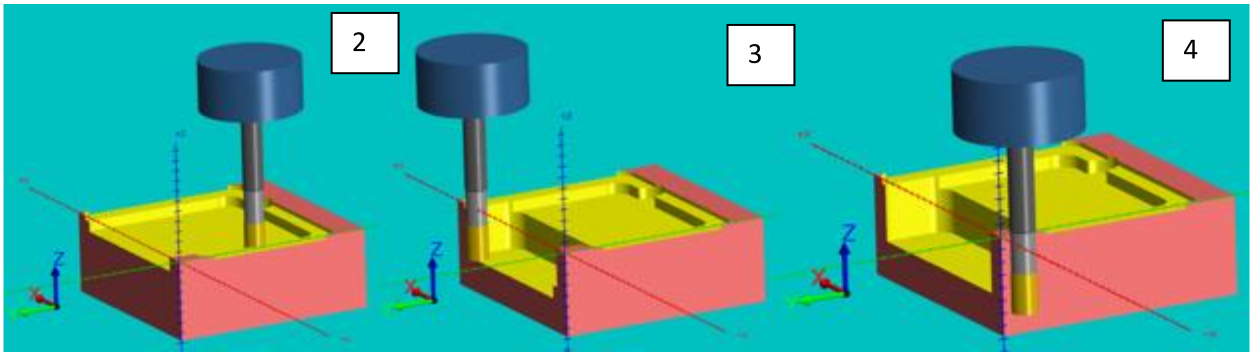


Figure 12 . Snipping Tool Image of Steps 2,3,4 Mastercam Tool Paths

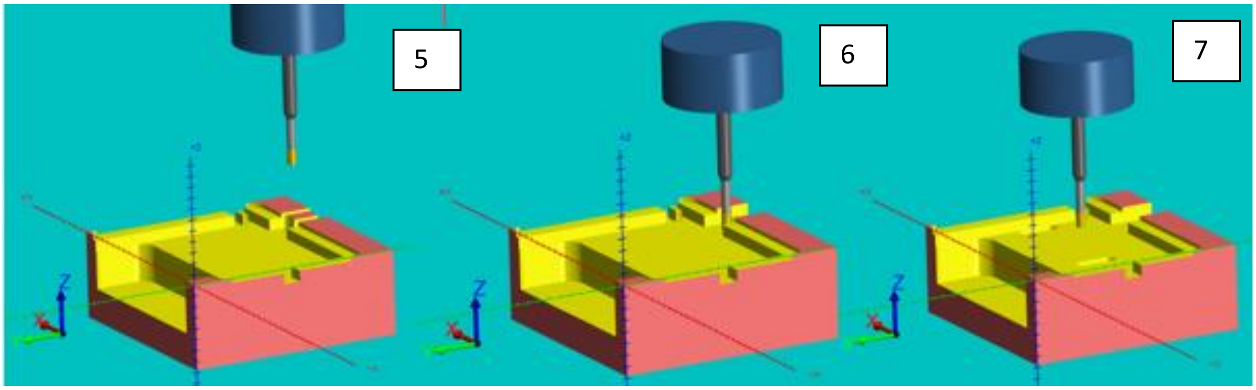


Figure 13. Snipping Tool Image of Steps 5,6,7 Mastercam Tool Paths

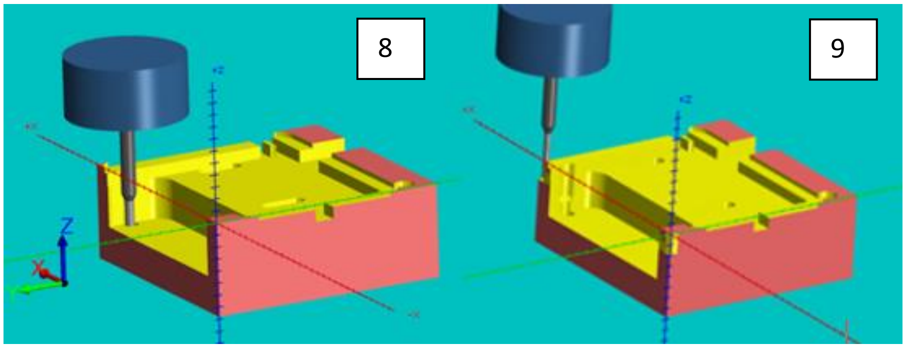


Figure 14. Snipping Tool Image of Steps 8,9 Mastercam Tool Paths

Steps 2, 3, and 4 are completed with the same 10 mm end mill of step one. Steps 5, 6, and 7 are completed with the 4 mm triple fluted end mill with the gearbox. Step 8 is completed with the 4 mm triple fluted end mill with the gearbox whilst Step 9 uses the 3 degree drafted end mill with 3 flutes.

3.1.8 Post Processing

Upon completion of the milling, the pieces need finishing of the surface. Due to the mill cuts the surface is fluffy and electrostatic with the cut foam. Consequently, the surface is sanded lightly. The surface is then hardened with a hot air gun at 300 degrees Celsius for a few seconds per side. See figure 15.

Figure 15. Hot Air Gun in Use

As a result of the vacuum table the holes for the screw towers and electronic connections could not be completed by the mill or the vacuum would be lost. Therefore the holes leave a 0,2 mm bridge that is simply punched out with a drill bit by hand.

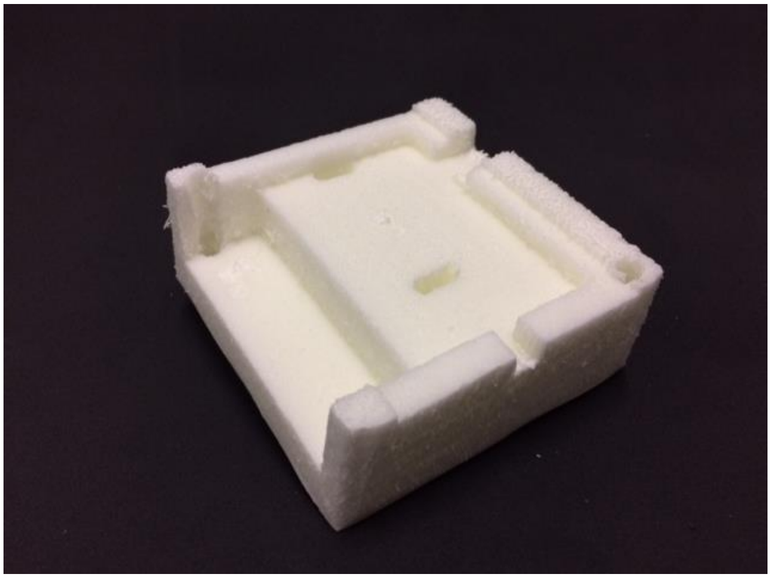


Figure 16. Final Milled Foam

3.1.9 Density

As the manufacturer specified this 32 kg/m^3 it is easy to calculate the foam density via equation 10 as Polystyrene has a density of 1050 kg/m^3 (Crow, 2016):

$$R = \frac{\rho_f}{\rho_P}$$

$$R = \frac{32}{1050}$$

$$R = 0{,}03$$

3.1.10 Mass Production Cost Calculation

The material cost is calculated as follows:

Size needed per piece 120 x 120 x 38 mm

Size of sheet 50 x 600 x 2500 mm

Therefore (600/120) x (2500/120) = 625 units per sheet costing € 13,90

13,90/ 625 = €0,02224 per unit

According to a company quote, the cost of milling for varying quantities ignoring material cost is as follows in table 2:

Table 2. Cost of Outsourced Foam Milling

Quantity	€ /unit	€
10	46	460
100	22	2200
500	16,5	8250
1000	11	11000

3.1.11 SWOT Analysis

The milling of foam pieces has shown some great potential yet still holds many weaknesses to be discussed below in the SWOT analysis (see section 2.22 for more details on SWOT).

Strengths

The internal factors of this production method revolve around the advantages of short run manufacturing as outlined below.

Cost

For short run production, the cost is relatively cheap as the material is easily available and each item can be changed without a significant increase in cost.

Individualisation

As the HAAS milling machine mills out each piece separately according to the G-Code, then each piece can easily be modified. This is especially relevant for developing the optimal shape.

Time

Erland Nyroth programed the machine to produce an array of 6 in just 14 minutes averaging just 2 minutes 20 seconds each piece of milling time, add in on the tool changes, stock set-up and piece removal, the pieces can still be produced in around three minutes (neglecting post processing).

When considering post processing of sanding and the use of hot air, an estimate of 5 minutes per piece is used resulting in 12 units per hour once the correct tool paths and G-code are created.

Immediate Testing

As the pieces are milled in house at Arcada then the pieces can be examined and tested immediately so in the development of the optimum design, change can be made immediately and new G-code produced. This is especially relevant when comparing to an outsourced method that could easily require a two day postage post production.

Material Choice

As milling machines can process a large variety of materials especially those of closed cell foams, then the optimum material can be selected from a larger library than other manufacturing means such as reactive injection moulding. For this specific situation, thermally insulating foam had been selected.

Weaknesses

Conversely to the strengths, the internal weaknesses of milling revolve around the shortcomings of short run manufacturing as discussed below.

Cost per item

As extensive work is required per piece produced with programing, milling and post production, the cost per piece is relatively high when larger quantities are needed. At a quantity of 10 the cost is a staggering €46, but by 100 units the cost per unit is an affordable €11.

Post processing needed

Unfortunately upon removal from the vacuum table each piece of the array of six needed to be cut out, the surface needed to be sanded then blasted with the hot air gun and finally the holes for the screw towers (and electronics) needed to be punched out. This is a real disadvantage as other manufacturing methods are ready to use upon removal from the machine.

Finish

The surface finish is far from desirable as post milling it is ‘fluffy’ and electrostatic. Upon post processing the surface no longer holds fluff but is very rough. As the foam is to be covered by a thermoformed case it is not a huge problem for the application however it does lack the last refinement needed for a professional impression.

Base is tacky from sealing tape

As a result the vacuum table design, extra vacuum tape is needed with a rubber seal to maintain suction. This tape is then stuck to the base of the foam. There is no need to remove the sticky tape as it doesn’t impede the functionality of the pieces. However, the tape does impact the presentation of the foam.

Waste

As this manufacturing method relies on removal of material, the material that is removed is waste. As a result of the material forming dust rather than chips the material has to cleared with a vacuum cleaner and cannot be re processed and used. Having said that, the waste material can be regained as energy as it is a polymer. The slab is 50 mm high and needs to be cut on the band saw in the x and y direction resulting in a total estimated waste of 40 %. Having said that, as the density is so low and the financial cost is minimal the waste material is likewise negligible.

Opportunities

The external opportunities of this manufacturing method allow for the development and refinement of milling allowing for cheaper, cleaner and more refined products.

Larger array in larger machine

As much of the time is taken in tool changes or placing the stock in place. Time and money can be saved if more foam pieces are produced in one series. Unfortunately the vacuum table dimensions limit this and even if it didn’t the milling table is limited to 300 x 600 mm. If outsources a larger array of 5 x 5 may be utilised in order to minimise time and cost.

Automatic post processing

If mass production was required by this method then automatic post processing of sanding and hot air can be implemented.

Develop sealing system with O ring so no tape is needed.

For a professional finish on the base then large O-rings can be used instead of the ribbon to maintain minimum loss of suction and would not require any sticky vacuum tape.

Personalise each piece, eg. with a reference number

As all foam pieces can be made with varying dimensions then it reasons that each piece can be made with an individual serial number. This number may be useful when assuring the correct reference pin is connected to the correct meter. However, as each meter case has an individual sticker number to linkup with the meter and pin, then personalising the foam is unnecessary.

Threats

The external element of threats rely on the other methods examined in this thesis of: EPS and DIY casting. However, it is also fair to consider carving out the pieces completely by hand. The foam responds positively to the scalpel blade and if an individual piece is required, then it stands to reason that it can be cut by hand. In continuation to subtractive manufacturing methods. Foam is an excellent material for hot wire cutting where a current is passed through a wire with high resistance that then heats up and is able to slice through foam like a hot knife through butter.

3.1.12 SWOT Milling Summary

Table 3. SWOT Milling

INTERNAL	**External**
Strengths • Cost • Individualization • Time • Immediate Testing • Material Choice	Opportunities • Larger array • Automatic post processing • Develop sealing system with an O-ring so no tape is needed • Personalise each piece, eg. with a reference number
Weaknesses • Cost per item • Post processing needed • Finish • Base is tacky from sealing tape • Waste	Threats • EPS • DIY Casting • Carving • Hot wire

3.2 Foam Expansion via DIY Method

3.2.1 Method and Expectations

DIY method refers to ‘do it yourself’ with the idea that anyone can complete it at home or in their shed. For this section of the thesis it is slightly more complex as it relies on the school’s restrictions rather than an individuals. This is particularly relevant when it comes to the production of the pattern.

The reason for this venture is to prepare the student to produce an EPS mould design. The design will not be produced due to the high initial cost, however the preparation via DIY will allow for the design to be on call if the need arise for an EPS moulded mould. However, this venture also offers information for the possibility of short run moulded foam and produces an interesting comparison to other means of foam production.

3.2.2 Restrictions

The key restrictions to this means of production rest heavily upon demoulding requirements and the availability and cost of materials. A budget of 100 Euros has consequently been set and the mould needs to be flexible enough to withdraw the columns to form the holes. It is also feasible that the foam will either expand too much or shrink significantly upon curing producing inappropriate forms.

3.2.3 Material and Properties

The material of choice was a store bought polyurethane foam intended for filling gaps in walls. The material is sold in a can and produces 22-28 litres.

3.2.4 SolidWorks Design

Considering the restrictions examined above, the piece was redesigned in SolidWorks with radii on all edges. As it is unknown whether the foam is easily pierced by the electric pins under the switch, a cutout was designed. The pins behind the screen have not been accounted for as it is expected that the expanded foam will allow some give and will consequently align the top circuit board. The tab above the battery holder by the PCB has been excluded from the design as the detail is too fine for foam expansion. The holes for electrical connection between the PCBs have been realigned so as the construction is more accurate and faster. See figure 17.

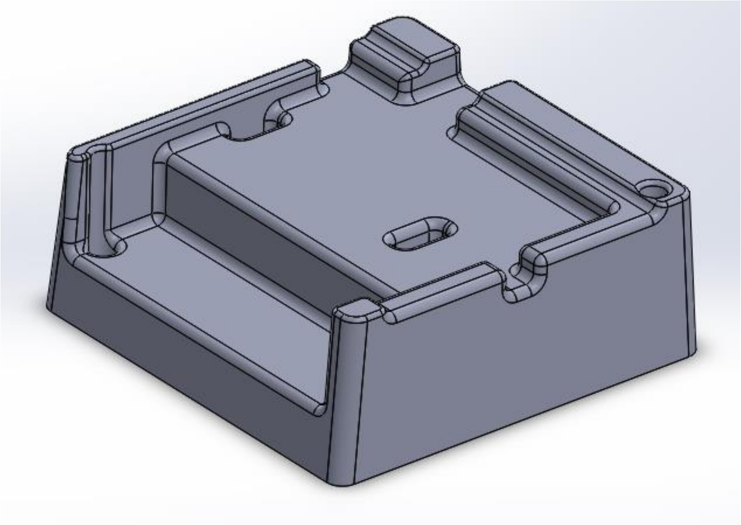
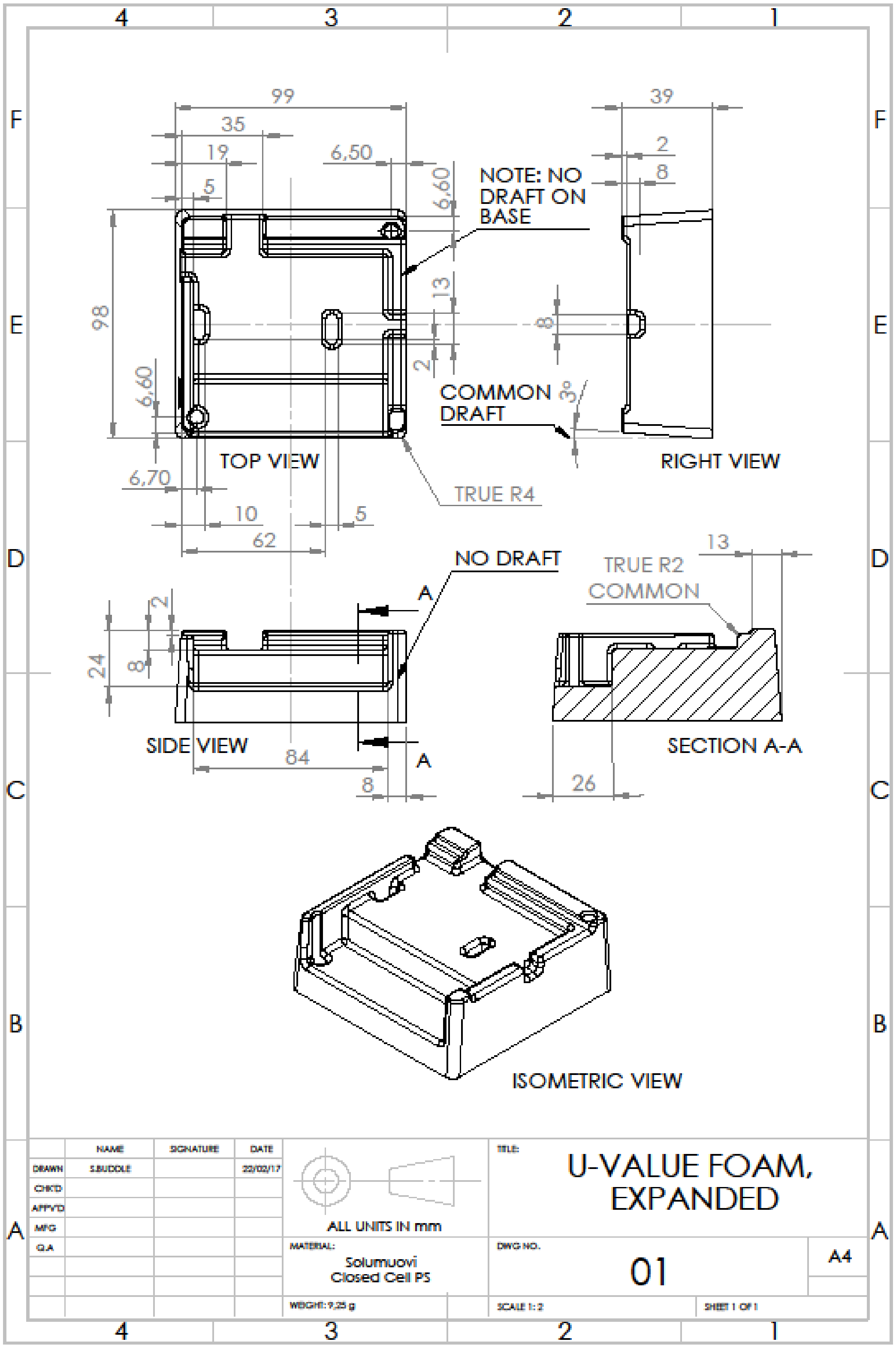


Figure 17 . SolidWorks Design for Foam Expansion

The piece is produced in SolidWorks exactly the same as previously with the use of extrusions, extrude cuts and fillets. See section 3.2.5 below of the technical drawing of the piece on the following page.

3.2.5 Technical Drawing of DIY



	NAME	SIGNATURE	DATE
DRAWN	S.BUDDLE		22/02/17
CHK'D			
APPV'D			
MFG			
Q.A			

ALL UNITS IN mm

MATERIAL: Solumuovi Closed Cell PS

WEIGHT: 9,25 g

TITLE: U-VALUE FOAM, EXPANDED

DWG NO. 01

A4

SCALE 1: 2

SHEET 1 OF 1

3.2.6 Printing

The pattern was shelled inward to minimise wasted resin and printed via SLA (stereolithography) printing on Arcada's FormLabs Form2 in white resin. The material choice is white resin2 due to it's rigidity and availability at Arcada. The layer height was set to 0,1 mm, the largest height available as the detail does not need to be flawless for this form as the foam itself will not be flawless either. See figure 18 below.

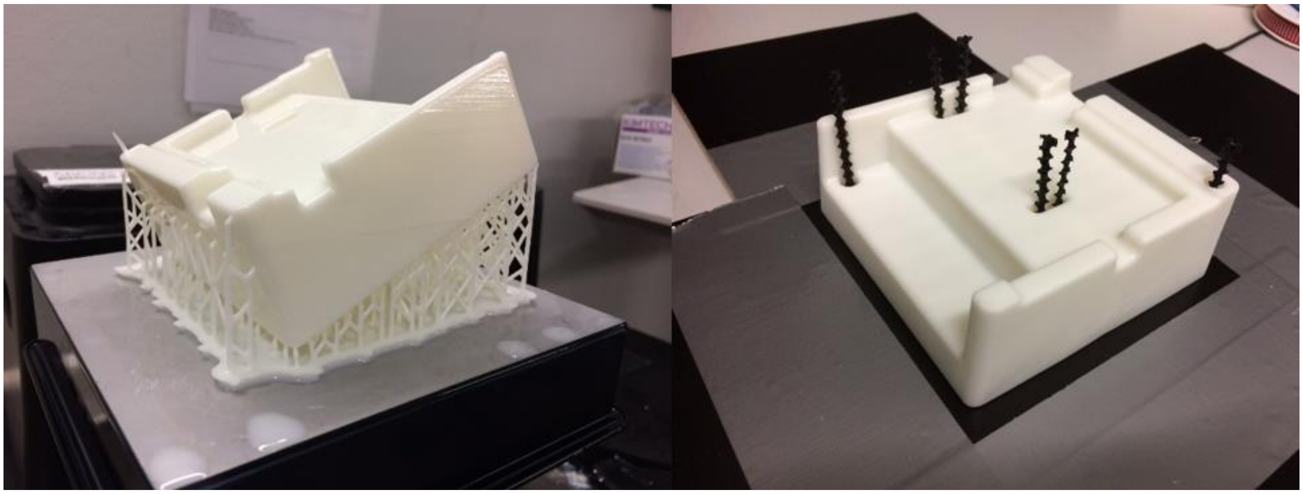


Figure 18. SLA Printed Pattern with Supports (left), Prior to Silicone Casting (right)

The piece was printed on a 30 degree angle with supports in order to prevent the overhung top surface from collapsing. It is expected that the silicone when casting will tear with the long thin rods to allow for holes to form. Consequently, rigid black support rods were used to sit within the casted resin. See figure 18. above right.

Upon completion of the print, post processing is necessary in order to finish the surface. This post processing involves submerging the piece in a two series bath of isoproponal the first 'dirty' one for 45 minutes and the second 'clean' one for five minutes. As a tacky layer is still present it is necessary to wash the surface with warm soapy water. The post curing time is 48 hours and the surface must be dry and non-tacky. The reason for a smooth surface is twofold; to cast a smooth surface on and prevent contamination of the curing silicone.

3.2.7 Mould Production

As there are thin towers for the screw towers and electronic connections to be made from silicone. Internal supports are to be made to hold the silicone upright. This is similar to steel in concrete. See figure 18. The printed piece needs to be secured to a plywood base with plywood walls with the following dimensions:

1400 x 1400 x 800 high = 1 568 000 mm^3

Whilst the volume of the pattern from SolidWorks = 267 000 mm^3

1 kg of silicone with unknown density, volume found from measuring the can

31 x 50 x50 x 120 = 943 000 mm^3

Therefore the silicone height is found by

140 x 140 x height – 267 000 = 943 000 mm^3

height = 62 mm

Making a theoretical 20 mm even wall on all sides and base of the mould. Silicone choice was Silicon NV purchased from a hobby shop for the reason it is self-degassing and designed for casting.

The silicone requires a 2% vulcaniser. As the whole weight of silicone is used, then

1010 g silicone / 98 x 2 = 20,6 g of vulcaniser for the 1010 g silicone

Mixed for 5 minutes then cast over the printed pattern. The silicone mould was left for 24 hours in a plastic bag in case of silicone leakage.

After 24 hours the plywood case is broken and the pattern removed see figure 19.

Figure 19. Cast Silicone (left), Final Mould (right)

3.2.8 Foam Production

The foam is injected into the silicone mould filling roughly half prior to the lid being clamped down. The optimum setting is 90 minutes in an oven at 50°C. They can then be removed from the mould. The pieces require a day to dry. The holes for the screw towers and electronics do not meet and are simply punched out by hand with a drill bit. A slight flash is removed from the base where the foam expanded through the part line.

3.2.9 Outcome

Both screw tower silicone columns failed (broke off) by 35 rounds. The mould is useable but extra post processing of drilling the towers is needed. By 42 units one of the two connection hole segments of the silicone mould broke making the mould unusable. However, the results are better than expected fitting nicely around the PCBs and within the case also. See figure 20. on the following page.

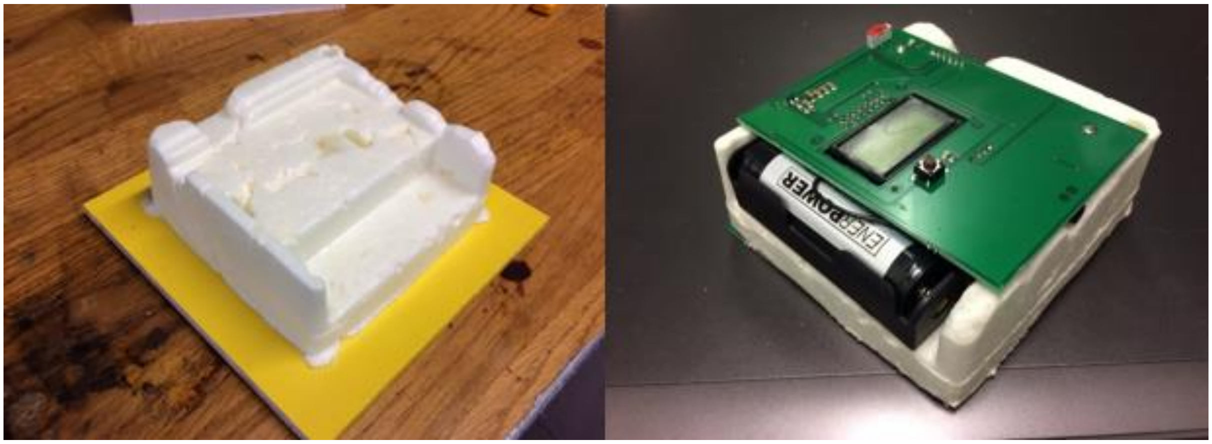


Figure 20. De-moulded Foam via DIY (left), In Use (right)

3.2.10 Cost and Density

The cost per piece is in relation to the longevity of the silicone mould and the cost of the 3D printed pattern and canned foam. One can costs €4,95 with 22-28 litres total (from package), estimate of 30% loss due to clearing the nozzle and excess foam released through air holes. The waste is irregular as it is dependent on the individual.

So, 0,7 x 25 = 17,5 Litres with an item volume of 267 000 mm^3. Therefore 17,5/0,267 = 65 units = € 0,076 per piece in material. Therefore, for a quantity of 42 (lifespan of the mould), the cost neglecting working hours is:

4,95 + 53 for the silicone = 57,95 total = €1,38 /piece.

Considering roughly every 40 cycles an extra three hours is required for casting new moulds, these costs are considered as follows with a salary of €20/hour:

40 cycles / (20 x 3) = €0,67/ piece

The cost including wage is as follows if €20/hour is considered:

€1,38 + 1,5 (hours) x 20 /4 (with a four part mould) + €0,67 = €9,55 / piece

The density of the piece is calculated to be 27,1 kg/m^2 as the pieces weigh 7,25 g and have a volume of 0,267 Litres. Therefore 7,25 / 0,267 = 27,1 kg/m^2.

The relative density from equation 10 is as follows:

$$R = \frac{\rho_f}{\rho_P}$$

$$R = \frac{27{,}1}{1020}$$

$$R = 0{,}062$$

3.2.11 SWOT Analysis

The DIY foam expansion of foam pieces has shown some surprising potential as the results are almost exactly what was desired. It stands to reason that there would have been unexpected shrinkage, issues demoulding and adherence to the mould could have made this manufacturing method a disaster. Nonetheless there are some issues with this method discussed below in the SWOT analysis.

Strengths

The internal factor of strengths of this production method revolve around the advantages of short run manufacturing as discussed below.

Easy

The process of producing the pattern by 3D printing holds some complexities as analysed above, however from the casting of silicone stage onwards the production process is incredibly easy with the materials all easily sourced from hobby shops or the hardware store. The method of injecting the foam via the can nozzle and placing a silicone sheet above was simple and required no expertise either.

Cheap

After neglecting the cost of the 3D printer in house (that was not purchased for this project) the cost of materials was exceptionally cheap with each can costing less than five euros and the mould costing round

50 Euros. If the pattern cost needed to be calculated for outsourcing as it is not a normal home appliance, the cost would still be less than 150 Euros.

Surface Finish

Relative to milling analysed previously, the surface finish of DIY expansion is immaculate. The surface is smooth as a hardened layer formed on the surface as it made contact with the silicone mould.

Material Choice

Although the material choice options are limited by the availability of varying foams, one option available is a fire retardant foam intended for insulating walls with a fire danger. This is significant as although the U-Value Meters are not to be used in these severe conditions, if a short were to happen on one of the circuit boards then the danger would not carry throughout the meter.

Cost Excluding Wage

The meters are incredibly cheap when excluding the cost of the manufacturer. As it is a DIY method the wage of the person making the pieces is not considered as it is something that can be done at home in their own time. Therefore the cost per piece is only 1,38 Euros per piece excluding the cost of the pattern. Having said that, when the wage is considered then the cost is € 8,88 with a four cavity mould.

No Post Processing

In contrast to milling no post processing of the surface is needed, it is removed from the mould smooth and finished.

Weaknesses

On the contrary to the strengths, the internal weaknesses of DIY expansion revolve around the shortcomings of the material.

Time

The production was optimised to a turnover of one every 90 minutes. This is incredibly slow when compared to the 2:20 minute production of the milled foam. If this method were to be used for a quantity of 100 then the time would be 150 hours, ie roughly one month. However, with a four cavity mould this would take a full week.

Surface Cavities

Although the surface is smooth there are some large cavities that formed due to the expansion of the foam and the skinning that consequently occurred.

Water Vapour

A small by-product of this method is water. This water is trapped within the cavities, as it is a closed cell foam however this water vapour is minimal.

Bulging at the sides

As a result of the pressure of the expanding foam and the softness of silicone, when excess foam was injected the pressure causes bulging on all surfaces except for the base as it is in contact with plywood. This bulging I problematic as it prevents the correct construction of the meters.

Failing Towers

By 42 pieces produced, the mould failed beyond repair or fair use. This is a huge weakness as the mould lifespan is less than 50 cycles, comparatively less than other silicone moulds and especially to metallic injection mould moulds. The failed parts of the mould are the towers to shape the cavities for the screw towers and electronics.

Waste

As a result of the difficulty in measuring injected material release holes were made on the base. There was consequently an estimated loss of 30% material per unit. This loss is exceptionally high when comparing to EPS. Having said that, as the density is so low, the actual material loss is negilgable.

Cost Including Wage

The cost per unit including wage is comparatively high at € 9,55/ piece.

Post Processing

Although no post processing is required on the surface, processing is required on the screw towers and electronic connections to punch out the remaining material to allow for construction alike that of the milling.

Opportunities

The external opportunities of this manufacturing method allow for the development and refinement of foam expansion in relation to both the material and the mould design.

Two-part mould

The mould currently consists of a cavity and a flat wall. If the mould were to be made of two silicone halves the length of the screw holes would be halved consequently putting less pressure on each end of the tower.

More Cavities

If more cavities were to be made then the production time would be minamised per item. For example if a four cavity mould were to be made or four separate moulds, then the production time would be four per 90 minutes, ie. Every 23 minutes. Nonetheless the moulds would still fail over time and as the manufacturor's salary is not considered, there would be zero reduction in cost per item.

EPS

Although EPS is logically a threat to this production method, it is also an opportunity. The DIY method was developed to refine the design and prepare for the possibility of reactive injection moulding.

Threats

The external element of threats rely on the other methods examined in this thesis of: EPS and milling. It is also fair to consider other methods of DIY such as carving and the use of a hot wire as outlined under the threats to milling.

3.2.12 SWOT DIY Summary

Table 4. DIY

INTERNAL	**External**
Strengths • Easy • Cheap • Surface Finish • Material Choice • Cost Excluding Wage • No Post Processing	Opportunities • Two-part mould • More Cavities • EPS
Weaknesses • Time • Surface Cavities • Water Vapour • Bulging at the sides • Failing Towers • Waste • Cost Including Wage • Post Processing	Threats • EPS • Milling • Carving • Hot wire

3.3 Industrial Foam Expansion (EPS)

The key reason for analysing industrial foam production is to prepare for such a venture. The vast majority of foam used for packaging and electrical insulation in any form of mass production is via reactive injection moulding or steam. Consequently, the ideal outcome of the method is to have a design ready for steam moulding for expanded polystyrene (EPS).

3.3.1 Restrictions

Due to the milling requirements of the mould the minimum radii is 2 mm and there cannot be any undercuts as is the case with the milled foam and DIY method.

It is preferential to design the mould so milling is only required on one face (mould part) as the less milling of the mould results in a lower cost.

A draft of three degrees is needed for demoulding.

3.3.2 Design

The design used by the DIY method was developed for the tooling restrictions of reactive injection moulding. Consequently the design is identical to that in section 3.1.4

The design was developed so as the shape could be milled out of a single mould halve with a flat back plate.

3.3.3 Density

Unfortunately as the pieces have not been produced it is impossible to calculate accurately the relative density, however as (EPS, 2014) states that EPS is 98% air then the relative density R in respect to equation 10 is 0,02.

3.3.4 Plan for Production

A company was contacted and the design restriction (as explained above) were discussed. They recommended a four cavity mould and recommended a minimum order of 1000 to offset the cost of 6500 Euros for the mould. The material choice for industrial foam expansion is polystyrene as it is standard for this means of production and it was recommended by the company.

The design illustrated on in section 3.1.4 was deemed appropriate and the company agreed to produce the mould and pieces once we required them.

Unfortunately as the final method for production has not been produced, only proposed it is very difficult to analyse and compare to the other methods or production. This is especially true as the company is not only the producer of the pieces but the producers of the mould too. It is important to note that the student completing this thesis had no intention to design the mould or produce the pieces, only develop a design and establish the manufacturing method's feasibility to produce such pieces. Nonetheless, the following SWOT analysis has been completed on the expectations of such a manufacturing method.

3.3.4 SWOT EPS

Strengths

As steam EPS is the standard production technique for small foam items in large quantities, the internal strengths rest heavily on those of mass production in contrast to the DIY method examined previously.

Large quantity quickly

For EPS the cycle time is typically counted in the seconds, for items of this size a series of four could be produced every 40 seconds easily, resulting in 100 produced in less than 17 minutes. If an even larger quantity is needed, it is an incredibly easy upscaling process as the moulds should holdup for 100 000 cycles producing four times that (as it is a four part mould).

Cost (Large Quantity)

The cost for a large quantity is incredibly low with each piece costing just 0,55 € for a quantity of 1000 and 0,42 € beyond 15 000 pieces. Of course the cost of the initial mould of € 6 500 equates the cost per item (for 100 pieces to) 6500 / 1000 + 0,55 = €7,05.

No post processing

Mass production methods are optimized to require as little post processing. If post processing is used it is usually automated, such as surface treatments. However in this method of producing these foam pieces there should be no need whatsoever for any processing.

Smooth Surface

As a result of the pieces being made by expanding into a mould, it is expected that the pieces would yield a slight skin creating a smooth surface.

Consistency

Once again, as it is mass production, then it is expected that this method produced the most consistent pieces.

Minimal waste

The process is designed to optimise material as on each cycle the precise volume of material is used. The only waste possible is in the optimisation stage resulting in an estimated three percent waste. The lowest by far of all the manufacturing methods.

Weaknesses

On the contrary to the strengths, the internal weaknesses of EPS revolve around the shortcomings of the material.

High Initial Cost

Unfortunately as the method requires a functioning mould, the cost of producing one item is staggering at 6500.

Mould Production Time

Prior to the first piece being made the mould itself needs to be milled and constructed usually taking weeks as the raw materials of the mould need to be sourced even before the metal (usually aluminum) is milled.

Postage

The production is also not local (in Muurla) so the results are not immediate with expected postage of two days.

Sameness

Mass production always struggles with variety; consequently, it is impossible to vary each piece such as adding a series number. This is still true with this manufacturing method. In continuation if an error has been made in the design it cannot easily be fixed. An error in design will require a minimum of re-milling the mould, potentially replacing the entire mould, in this case costing 6500.

Large Minimum Order

Fast mass production has it's downsides when it comes to small orders, the company The company recommends a minimum quantity of 1000 units. It is feasible they could produce less however a single cavity mould would be used and the cost per item would be excessive.

Limited Material Choice

In this specific example due to the thin sections the company only recommends small grain EPS the material is appropriate however, if another material perhaps urethane were to be desired, then it is not a feasible manufacturing method. Having said that, EPS is UV resistant as opposed to PU.

Opportunities

The opportunities of this manufacturing method are difficult to predict, as the method is only a proposal. In continuation, the manufacturing method is already set up for optimal production, hence why the industry exists. Nonetheless a few possibilities are notable.

More cavities

Steam moulding is comparatively outstanding for producing many pieces in a single machine per cycle. The recommendation is currently a four cavity mould, but assuming the machine is large enough with a large enough clamping force there is no reason why a 16 cavity mould could not be used.

Cheaper Production Location

If the items were to be made in a cheaper location the cost of the mold and material could be minamised. Having said that, the most obvious location of China is relatively far away and the cost of postage (shippage) would increase. It is important to note that the pieces are mostly air so the space required to ship them would be huge potentially costing more per item.

Threats

The external element of threats rely on the other methods examined in this thesis of: DIY and milling. It is also fair to consider other methods of DIY such as carving outlined under the threats to milling.

3.3.5 SWOT EPS Summary

Table 5. SWOT EPS

INTERNAL	**External**
Strengths • Large quantity quickly • Cost (Large Quantity) • No post processing • Smooth Surface • Consistency • Minimal waste	Opportunities • More cavities • Cheaper Production Location
Weaknesses • High Initial Cost • Mould Production Time • Postage • Sameness • Large Minimum Order • Limited Material Choice	Threats • Milling • DIY Casting • Carving

4. Results

The results revolve around the comparison of the SWOT analyses and a cost comparison with an emphasis on the advantages and disadvantages of short and long run manufacturing. Initially the qualitative results are examined from the SWOT analyses prior to the quantitative data analysis of time and financial cost.

4.1 SWOT Qualitative Results

The SWOT analyses for each individual method considered costs in terms of time and money, however these are explored in the following section. Consequently the remaining qualitative issues include the issues of individualisation/consistency, materials, post processing, surface finish, quantities and waste.

Prototyping and Consistency

The short run manufacturing methods of milling held a great advantage of individualisation, making that method superior in concept generating, however the DIY method despite being a short run method did not. For the EPS method, individualisation was not feasible; however it would most likely hold the most consistent results. This is especially true when comparing to DIY as the sides occasionally bulged out and cavities were visible.

Material Variety

In respect to material choice milling was by far the most superior as virtually any foam can be milled assuming it can be held by the vacuum table. The DIY method had some advantages when it came to materials as a fire retardant option was available. In continuation, the EPS was least desirable as only one form of small grained polystyrene was appropriate. Having said that, small grain PS is a very appropriate material due to its insulation properties.

Post Processing

For post processing the EPS method was found to be best as no processing of the surface or screw towers is needed. The DIY method had some attributes as although the screw towers needed to be punched out, the surface was relatively smooth. At the far end was the Milling as the screw towers needed to be punched out and the surface needed to be post processed.

Surface Finish

The surface finish of the EPS is expected to be most desirable as it is expected to be smooth and without cavities. The DIY method is in the middle as it formed a smooth skin however larger cavities were observed. The surface finish of milling is last as it rough upon post processing.

Quantities

When examining quantities none succeeded with the specified quantity of 100 this is as a result of the gap between short and long run manufacturing methods.

Waste

It is expected that the EPS method produces the least waste as the means is designed to be optimised in regards to waste, ie. with precise measurements. With regards to DIY roughly 30% waste is produced and Milling at 40%. The massive loss with milling is due to the fundamentals of subtractive manufacturing and in regards to DIY the inefficiencies of measuring.

4.2 Quantitative Time and Financial Cost Results

The time and financial cost results use quantities if they are to be all outsourced. This was chosen as not all manufacturing methods can be made at Arcada. It was decided to choose two timeframes that of short run and long run, ie. with quantities of 1-100 units and 100-1000 respectively. With results from the short run all data was considered to build the results, for example the time needed to source materials. However as it is expected for mass production that the purchasers are aware of this time then it was not accounted for.

4.2.1 Cost Comparison Short Run

Consequently, for a short run financial cost comparison it was found that the DIY method was most affordable. See figure 21 below. The costs are displayed in Table 6 (right) and were concluded via the following equations:

Milling See section 3.1.10

DIY 150 (pattern) + 53/42 (silicone) +

30/4 (wage)

=150 +9,55 x Qty

EPS 6500 (mould) + Qty x 0,55

Table 6. Short Run Cost Comparison

Quantity	Milling	DIY	EPS
10	460	238,4	6505,5
20	660	326,8	6511
30	860	415,2	6516,5
40	1060	503,6	6522
50	1260	592	6527,5
60	1460	680,4	6533
70	1660	768,8	6538,5
80	1860	857,2	6544
90	2060	945,6	6549,5
100	2200	1034	6555

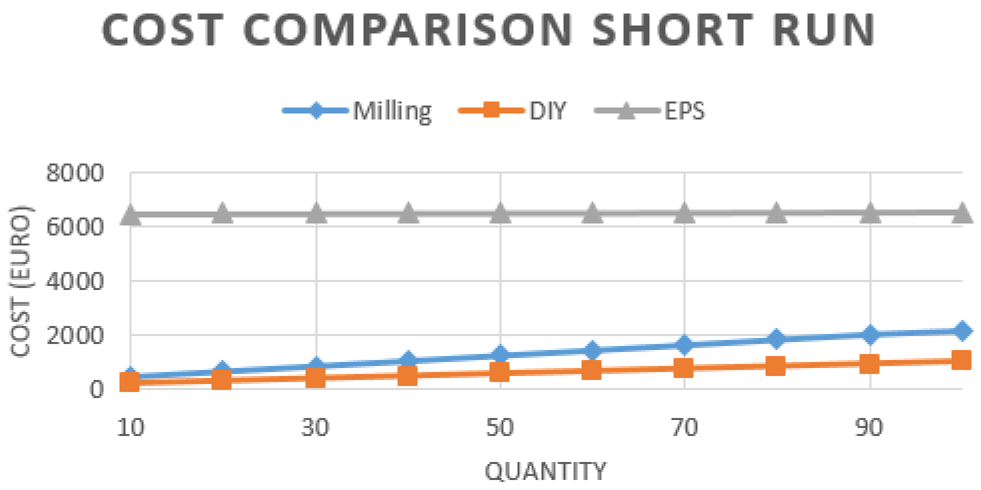


Figure 21. Graph of Short Run Cost Comparison

It is clear that the initial financial cost of the EPS mould is completely unrealistic; however, both milling and DIY are feasible.

4.2.2 Cost Comparison Long Run

For a long run financial cost comparison, it was observed that the EPS method was most affordable from a quantity of roughly 600. See figure 22 below. Having said that, if a quantity of 100 is needed and the only consideration made is financial cost then clearly DIY is most feasible. The costs are calculated via the following equations and represented in table 7.

Milling	See section 3.1.10
DIY	150 + 9,55 x Qty (see cost comparison short run)
EPS	6500 (mould) + Qty x 0,55

Table 7. Long Run Cost Comparison

Quantity	Milling	DIY	EPS
100	2200	1034	6555
200	3700	2068	6560,5
300	5200	3102	6566
400	6700	4136	6571,5
500	8250	5170	6577
600	8800	6204	6582,5
700	9350	7238	6588
800	9900	8272	6593,5
900	10450	9306	6599
1000	11000	10340	6604,5

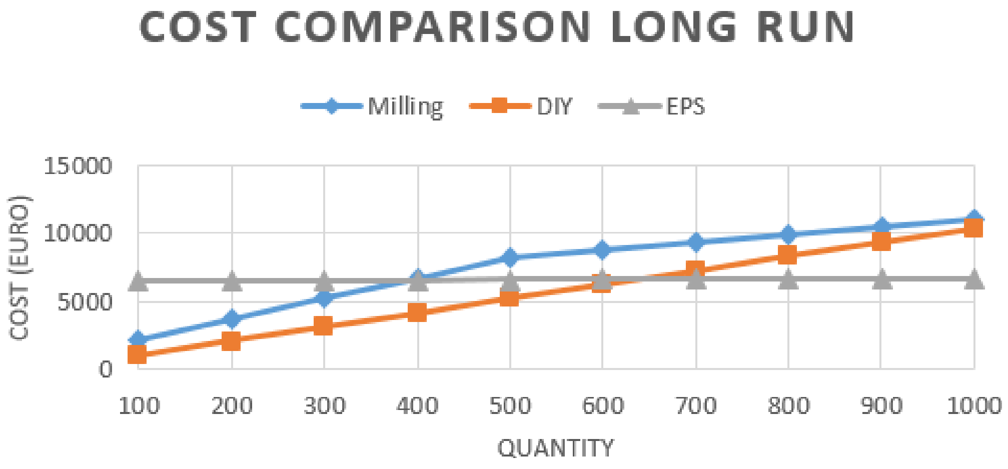


Figure 22. Graph of Long Run Cost Comparison

When considering cost alone, both Milling and DIY are most affordable however after 600 units EPS is the most affordable.

4.2.3 Time Comparison Short Run

When only time is considered in a short run perspective the time of manufacturing the moulds and postage etc. are taken into account as short run works in the present to fulfil current orders. Consequently the values in hours are calculated via the following equations and represented in table 8.

Milling	2 (source materials) +
	Qty. x 0,038 (time of milling)
DIY	80 (pattern) + 8 (casting silicone) +
	Qty. x 1,5/4 (casting)
EPS	38 x 3 (mould production) +
	Qty. x 0,0027 (time of production)

Table 8. Time Comparison Short Run

Quantity	Milling	DIY	EPS
10	2,38	91,75	114,027
20	2,76	95,5	114,054
30	3,14	99,25	114,081
40	3,52	103	114,108
50	3,9	106,75	114,135
60	4,28	110,5	114,162
70	4,66	114,25	114,189
80	5,04	118	114,216
90	5,42	121,75	114,243
100	5,8	125,5	114,27

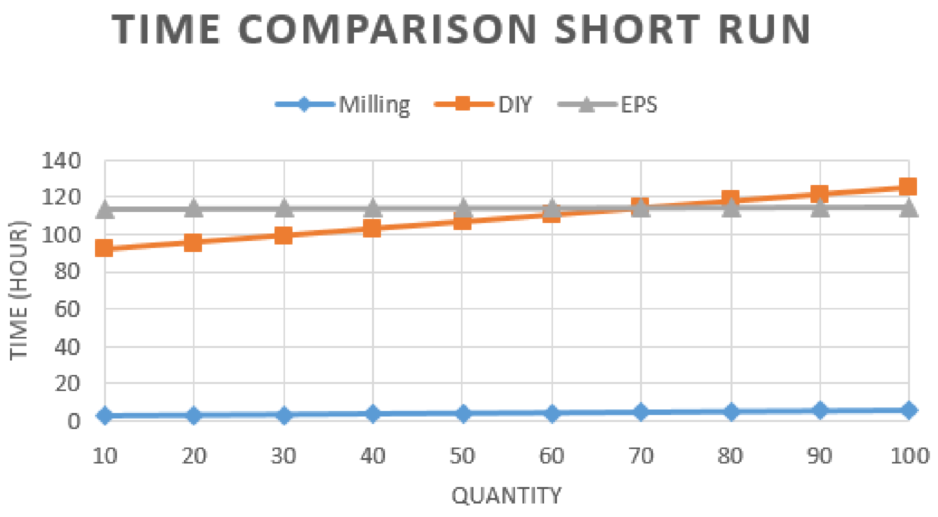


Figure 23. Graph Time Comparison Short Run

From figure 23. It is clear that if only a short timeframe is considered, then milling is by far the best taking virtually seconds per piece.

4.2.4 Time Comparison Long Run

The long run time considerations neglect sourcing of tools and materials as good planning takes into account tooling and sourcing before the need. Also, as a business works in the desired order mindset as opposed to the current order mindset, the only consideration is the time per piece. The values are calculated via the following equations and represented in table 9.

Long Run Time Comparison

Milling Qty. x 0,038

DIY Qty. x 1,5/4 = 0,375

EPS Qty. x 0,0027

When planning is considered (see figure 24) the timeframe of EPS is by far the most affordable with DIY off the scale at a quantity of 400 and milling gradually taking more and more time compared to EPS.

Table 9. Long Run Planned Time Comparison.

Quantity	Milling	DIY	EPS
100	3,8	37,5	0,27
200	7,6	75	0,54
300	11,4	112,5	0,81
400	15,2	150	1,08
500	19	187,5	1,35
600	22,8	225	1,62
700	26,6	262,5	1,89
800	30,4	300	2,16
900	34,2	337,5	2,43
1000	38	375	2,7

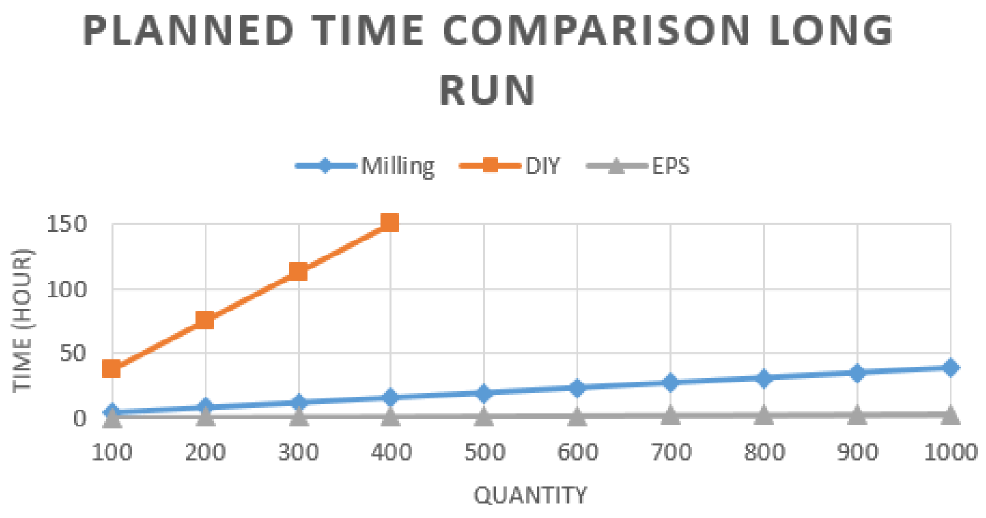


Figure 24. Long Run Planned Time Comparison

4.2.5 Cost x Time Short Run

To exaggerate the differences in time and money for each manufacturing method it was chosen to multiply the time in hours by the cost in Euros from the short run results. They are logically calculated as follows and represented in table 10.

Milling	short run cost x short run time
DIY	short run cost x short run time
EPS	short run cost x short run time

Table 10. Cost Times Time Short Run Comparison

Quantity	Milling	DIY	EPS
10	1094,8	21873,2	741802,6
20	1821,6	31209,4	742605,6
30	2700,4	41208,6	743408,8
40	3731,4	51870,8	744212,4
50	4914	63196	745016,2
60	6248,8	75184,2	745820,3
70	7735,6	87835,4	746624,8
80	9374,4	101149,6	747429,5
90	11165,2	115126,8	748234,5
100	1276	129767	749039,9

When time is accounted for the sourcing of materials, producing of the mould, etc. as is the case for the short run, milling is the most feasible, followed closely by DIY see figure 25 below. However due to the massive time and financial cost investment in the mould, EPS is far too expensive.

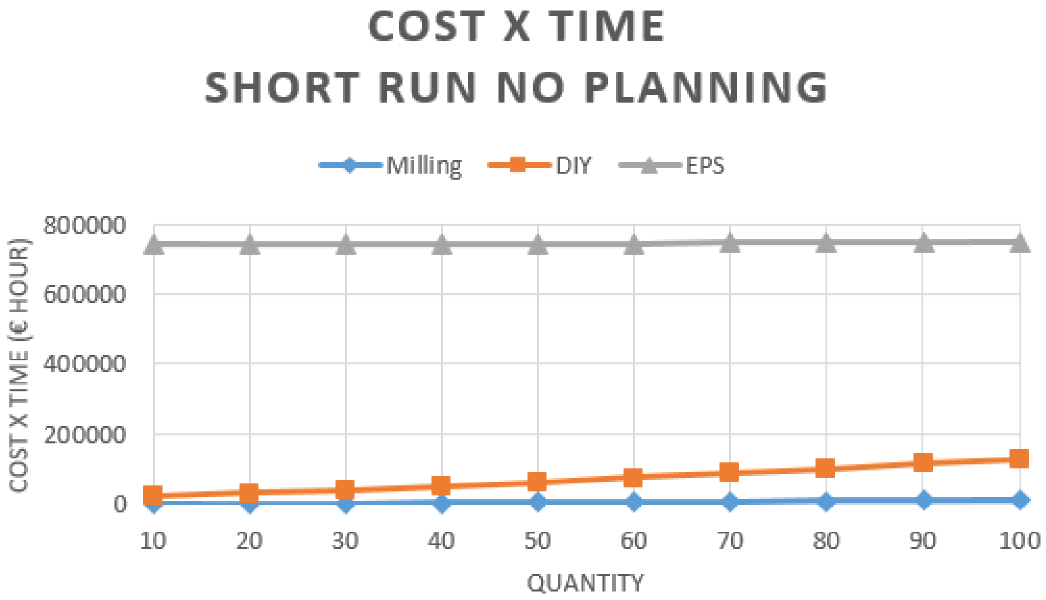


Figure 25. Cost Times Time Short Run Comparison

4.2.6 Cost x Time Long Run

As with 4.2.5, the results are multiplied to examine both time and financial cost simultaneously. However when considering the long run, the expectation is that the initial time investments are neglected as the company is working with potential or hypothetical orders. The values are calculated as follows and represented in table 11.

Milling long run cost x long run time

DIY long run cost x long run time

EPS long run cost x long run time

Long run planning neglects sourcing of tools and materials as good planning takes into account tooling and sourcing before the need.

Consequently when planning is respected the financial and time cost for mass production is most affordable by EPS as milling gradually increases whilst DIY quickly increases exponentially.

Table 11. Cost Times Time Planned Long Run Comparison

Quantity	Milling	DIY	EPS
100	8360	38775	1769,85
200	28120	155100	3542,67
300	59280	348975	5318,46
400	101840	620400	7097,22
500	156750	969375	8878,95
600	200640	1395900	10663,65
700	248710	1899975	12451,32
800	300960	2481600	14241,96
900	357390	3140775	16035,57
1000	418000	3877500	17832,15

Figure 25. Cost Times Time Planned Long Run Comparison

5. Discussion

5.1 Time and Financial Costs Discussion

The most interesting issue of this thesis is the quantity. Concepts or short run manufacturing up to 10 units offers varying manufacturing methods. These methods typically hold high costs per units, but require minimal upfront time and monetary investments. As is the case with milling the foam or DIY foam expansion. These methods struggle to hold up when larger quantities are needed in respect to time and cost. Comparatively to mass manufacturing of minimum orders of 1000 the initial time and money is huge but the running costs both in terms of time and money are marginal. The aim was:

"To select a mass manufacturing means for the U-Value Meter's internal foam with a primary focus on cost and time for 100 units."

Consequently, a dilemma is created as a quantity of 100 was needed. In this situation roughly half the cases were milled in house and half cast via DIY due to the staggering initial cost if reactive Injection moulding. Consequently both milling and DIY are feasible, however not optimal.

5.2 SWOT Discussion

In regards to the SWOT analyses, the comparisons revolve around the fundamental restriction of both short and long run manufacturing. These restrictions are as follows:

Short Run

Short run production is cheap for a few pieces, yet expensive for large quantities. From the short run methods of this thesis, the surface finish was found to be less desirable with high waste but better material choice.

Long Run

Long Run manufacturing is excellent with consistency but lacks the ability to make changes, it is also restricted with material choices. However the lack of post processing is a great asset to this manufacturing means.

5.3 Discussion Resolution

This situation leads itself open to development. Perhaps a manufacturing method could be developed to fulfil the needs of middle run productions requiring foam. Perhaps mould construction could be developed so a curing agent could be utilised in DIY without the need for high clamp forces to produce pieces in a matter of minutes, not hours. The silicone mould could also be developed as outlined in the DIY SWOT analysis to withstand 100 cycles, rather than just the 42 achieved. This area of interest could happily be continued by another student at Arcada.

6. Conclusion

In regards to the key criteria of time and money all three options are average at best at a quantity of 100 due to the reasons discussed above in regards to the gap between short and long run productions. Roughly half the foam for the metres was produced via each of the two short run methods in house at Arcada. Each method is feasible however; EPS is not due to the staggering initial cost. In continuation, EPS needed extensive preparation in order to guarantee the product is of the correct dimensions. However when multiplying the factors in figure 25. at a quantity of 200 there is already a clear successor, that of EPS. By 200 the DIY method is completely unrealistic due to time and milling is far too financially expensive. In sum, for a quantity of 100 units there is no ideal manufacturing means discovered.

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