Mechanical analysis

- Based on the material chosen, use the technical data sheet and use the material properties or characteristics in order to determine the max force and max stresses for the following load cases
    - Moment applied while turning the lid cap and the beam deflection of the small groove (max force/moment to be applied)
    - snap fit calculation (min/max force required) using this Link & snap fit PDF

Optimisation

If any reinforcements or additional processes are required for the chosen material to further improve the selection state and explain the choices as well as the impact it has on things such as price, density

Product assembly

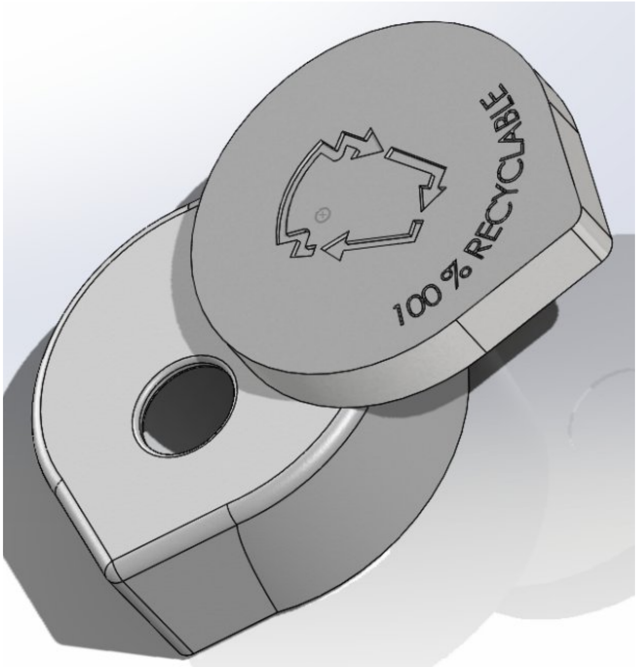


Fig 1 – Full cap assembly

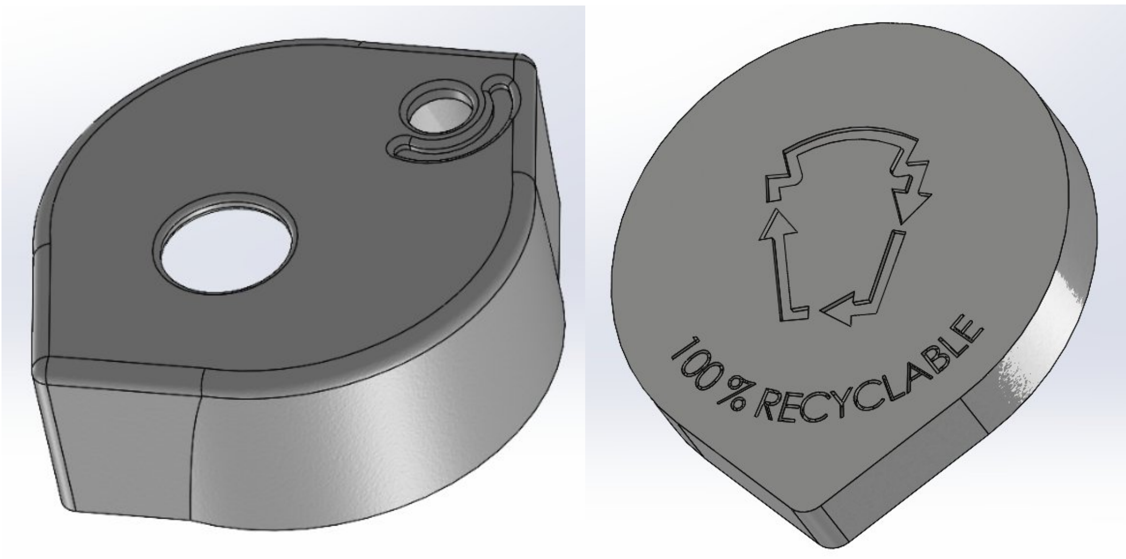


Fig 2 – Cap components, cap base (left) and cap lid (right)

Technical drawings

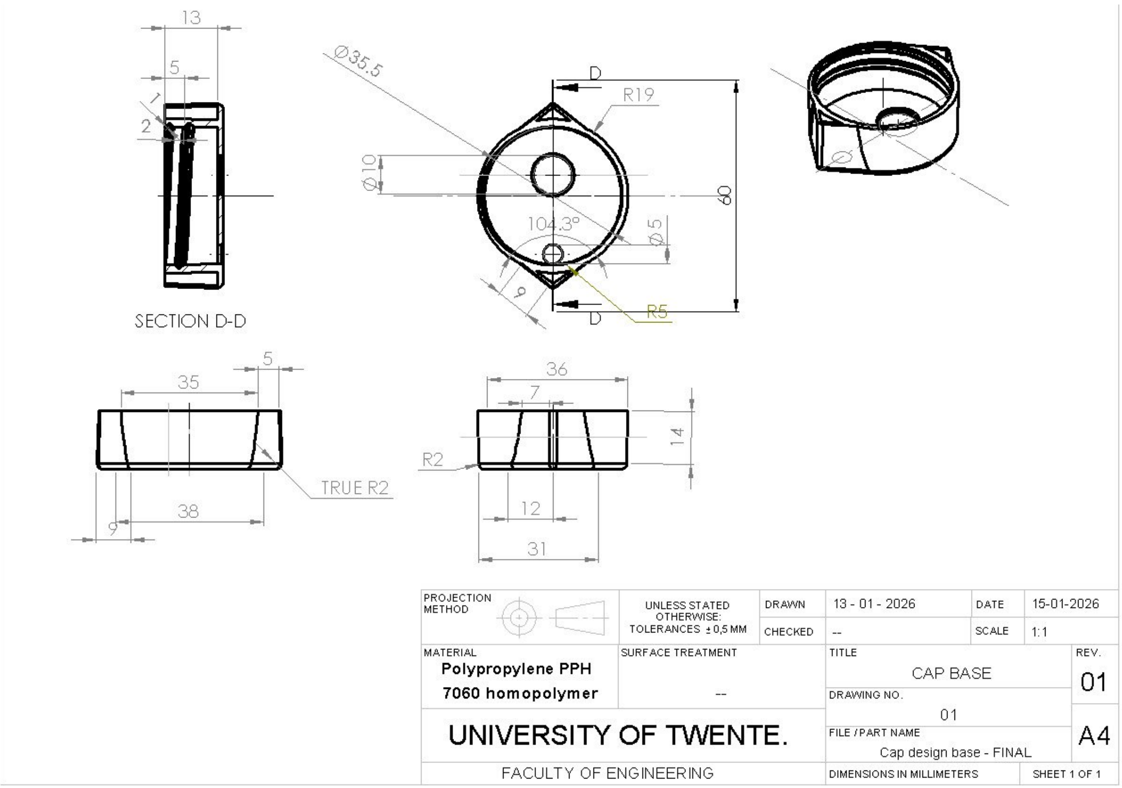


Fig 3 - Technical drawing cap base

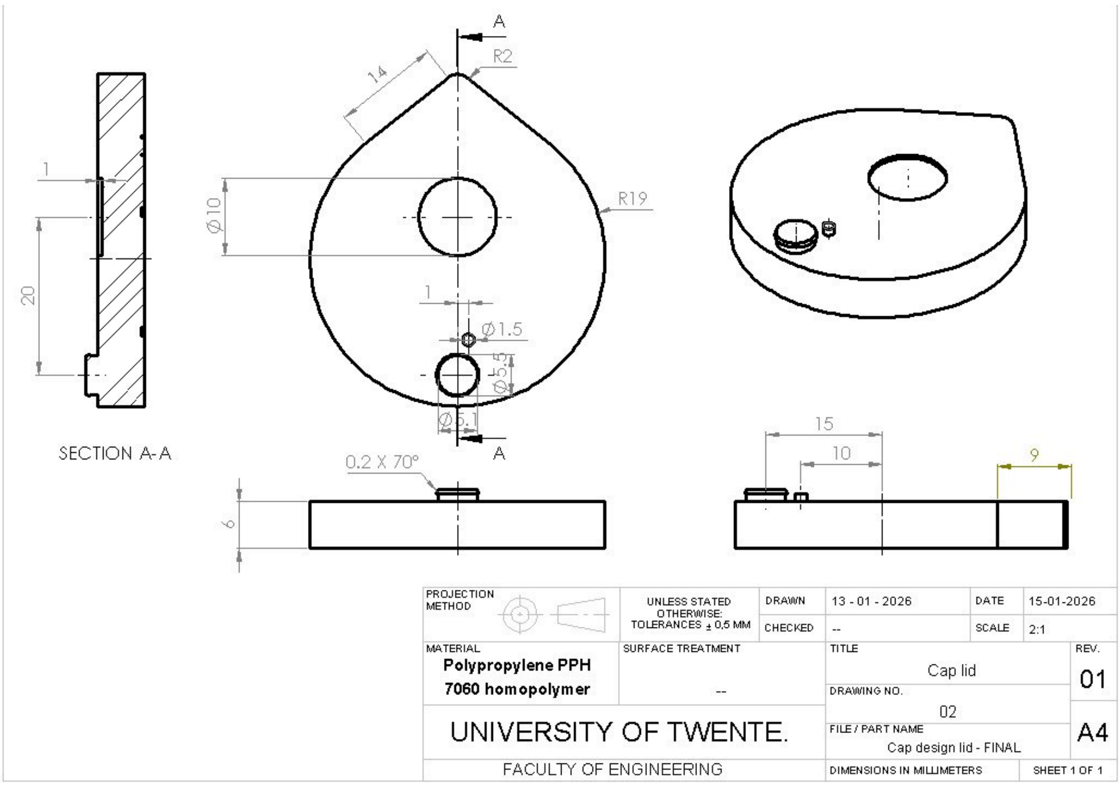


Fig 4 - Technical drawing cap lid

Material selection

The following section is regarding the material selection process for the chosen components. As the product is for condiment packaging, some essentials to consider are:

- Safety
- Chemical stability / resistance
- Impact resistance/durability
- Suitable for desired manufacturing process

As the material will be in direct contact with the condiment for a long period, it is crucial that the chosen material is not hazardous to human health and is chemically stable under this long exposure. The resistance to chemical change should be high and there should be no chemical mixing between the material and the condiment. It is also important injection moulding is a suitable and appropriate manufacturing process to create the condiment packaging.

Since plastics is a broad term, it can be narrowed down to 4 sub classifications: ultra-high-performance plastics, high performance plastics, engineering plastics and commodity plastics. The most suitable subcategory of plastics from which to select a material for condiment packaging is commodity plastics which includes packaging, bottles and disposable items.

Lid

Since the desired manufacturing process is injection moulding, and a lid is supposed to be recyclable, the most suited polymer would be thermoplastics. During the injection moulding process, thermoplastics soften under heat treatment however solidify once cooled.

1. PET (Polyethylene Terephthalate)

General Properties:

High strength and stiffness for commodity/engineering thermoplastic. It is also practical and is recyclable. PET also has good melt flow; however, unfilled PET is not suitable for injection moulding. It also has poor heat distortion temperature and high mold shrinkage.

Composition overview:

PET is a semi-crystalline or amorphous thermoplastic which can be transparent or opaque. Since amorphous grades have better clarity and barrier properties, additives which lower the crystallinity are added for production of transparent parts. Unmodified grades have high elongation, meaning its more ductile. Mineral filled grades can be used to counter the warpage and shrinkage at the cost of some strength being lost.

2. PP (Polypropylene)

General Properties:

High strength and high stiffness. Also has a higher service temperature and lower density. Also provides high durability against heat, impact and chemicals. Moderately high resistance to chemicals apart from fuels and provides good environmental stress cracking resistance. Good fatigue resistance and some grades are already approved for food packaging. This polymer does not dissolve in water.

Composition overview:

The composition of PP is semi-crystalline, and it is a thermoplastic. This means that it is highly stiff and strong.

3. PC (Polycarbonate)

General Properties:

High usefulness for engineering offered due to its properties over a wide temperature range. Needs additional properties, especially impact resistance. Not an ideal choice as the caps needs to be impact resistance throughout the mass transportation of condiment packaging.

Composition overview:

PC is a tough thermoplastic which is fully amorphous. PC is manufactured from BPA which is related to estrogenic effects at high doses. This limits the usability of this polymer as it’s not exactly chemically safe for the food packaging industry.

4. PE (Polyethylene)

General Properties:

Very cheap and offers good chemical and hydrolysis resistance. Also has high impact strength as low temperatures as well. The yield strength for this polymer increases with density. Also has a high tensile strength. Lower stiffness than PP and poor UV resistance so might not be a suitable choice for open transportation. The temperature for operating and heat distortion are quite low.

Composition overview:

This polymer is a semi-crystalline thermoplastic which is very good for injection moulding. This polymer is also chemically safe. However, due to low density, the polymer is somewhat ductile, making it harder for precise machining.

Selection matrix

Properties	Weight
Yield strength	3
Stiffness	4
Maximum service temp	3
UV resistance	2
Opaqueness	1
Sustainability	4
Density	4
Price	5

Table 1 – Weighing factors for the lid

	(Score) x (weight)			
Properties	**PET**	**PP**	**PC**	**PE**
Yield strength	4x3 = 12	4x3 = 12	5x3 = 15	2x3 = 6
Stiffness	4x4 = 16	3x4 = 12	4x4 = 16	2x4 = 8
Maximum service temp	2x3 = 6	3x3 = 9	5x3 = 15	2x3 = 6
UV resistance	3x2 = 6	3x2 = 6	3x2 = 6	2x2 = 4
Opaqueness	4x1 = 4	3x1 = 3	3x1 = 3	4x1 = 4
Sustainability	5x4 = 20	5x4 = 20	1x4 = 4	5x4 = 20
Density	3x4 = 12	4x4 = 16	2x4 = 8	5x4 = 20
Price	4x5 = 20	5x5 = 25	2x5 = 10	5x5 = 25
Total	**96**	**104**	**77**	**93**

Table 2 – Material selection matrix for the lid

Based on the results from the selection matrix, considering the weighing factors and how well the different polymers perform for that specific material property, PP is the most suitable and appropriate material choice for the cap of the condiment packaging.

Polypropylene (PP) is a semi-crystalline thermoplastic. It is widely used in the packaging industry especially in food packaging as well for caps and lids due to its good resistance to chemical changes. It is also relatively sustainable as well as a cheap option good for mass production. Some of the main strengths of using PP over the other 3 polymers include good toughness durability and resistance to elongations and the fact that injection moulding is highly compatible due to the stable flow characteristics [chinaplasticbottles, accessed 13/01/26]

Considering that the design has a snap fit, it's crucial that the material does not fracture due to being too brittle but is also strong enough to withstand high stresses without permanently deforming. For a snap fit, the part should bend elastically and reaches failure only when the elastic strain is exceeded. Hence to choose the correct composition of the chosen material, a performance index is used. The performance index favours polymers with a high yield strength and a low flexural modulus.

Performance index: $\frac{\sigma_y}{E_f}$

Since the general polymer is chosen to be PP, the different compositions of PP will be plotted according to the chosen performance index to provide the best possible compositions.

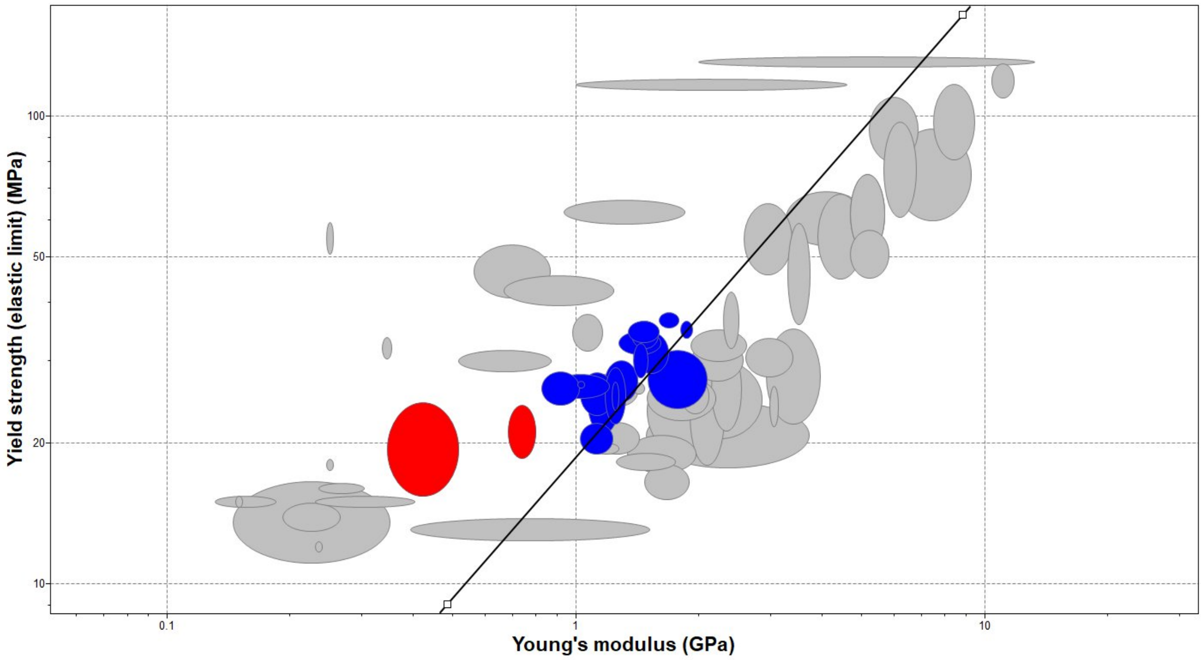


Fig 5 – Performance index graphed for most suitable material compositions

The results after plotting the different compositions yielded that the top 3 materials to be:

1) PP (copolymer, 10% talc)
2) PP (homopolymer, 10% calcium carbonate)
3) PP (homopolymer, 10% talc)

Homopolymer vs. copolymer

Homopolymer refers to the structure consisting of only monomers, in this case monomers of propylene. Due to this, the chains are linear and regular, which ensures high crystallinity of the material. It also has good chemical resistance however could be brittle in low temperature conditions.

Copolymer refers to the structure consisting of firstly propylene monomers along with another monomer which is usually ethylene. Copolymer has higher impact strength and flexibility. Copolymers also generally tend to not become brittle in low temperatures.

However, since the cap is designed to resist any leakages of condiment, and more importantly withstand the forces experienced on the threading, homopolymer is a more suitable choice. During crystallisation, chains are packed densely which reduce the volume. Crystalline polymers are also more susceptible to shrinkage and in extreme cases warpage or distortion due to high non uniform shrinkages. A lid must not deform too much but rather allow the desired deformation without experiencing any cracking. Between linear and branched molecular structures, a linear structure is preferred due to the high stiffness it offers. Branched polymers provide flexibility.

The 10% talc filled enhances the stiffness of the polymer as well as dimensional stability making it even more suitable especially for the forces the threads experience. However, the stiffness decreases due to the filling but it's not drastic, making this material still a suitable and appropriate material choice for the cap of the condiment packaging.

The chosen material is **PP (homopolymer, 10% talc).** The technical data sheet is linked below.

Data sheet: Link

Injection moulded preform

1. PET (Polyethylene Terephthalate)

General Properties:

High strength and stiffness for commodity/engineering thermoplastic. It is also practical and is recyclable. PET also has good melt flow; however, unfilled PET is not suitable for injection moulding. It also has poor heat distortion temperature and high Mold shrinkage.

Composition overview:

PET is a semi-crystalline or amorphous thermoplastic which can be transparent or opaque. Since amorphous grades have better clarity and barrier properties, additives which lower the crystallinity are added for production of transparent parts. Unmodified grades have high elongation, meaning its more ductile. Mineral filled grades can be used to counter the warpage and shrinkage at the cost of some strength being lost.

2. PP (Polypropylene)

General Properties:

High strength and high stiffness. Also has a higher service temperature and lower density. Also provides high durability against heat, impact and chemicals. Moderately high resistance to chemicals apart from fuels and provides good environmental stress cracking resistance. Good fatigue resistance and some grades are already approved for food packaging. This polymer does not dissolve in water. This material also has good moulded thread definition, which is important for a bottle.

Composition overview:

The composition of PP is semi-crystalline, and it is a thermoplastic. This means that it is highly stiff and strong.

3. PC (Polycarbonate)

General Properties:

High usefulness for engineering offered due to its properties over a wide temperature range. Needs additional properties, especially impact resistance. Not an ideal choice as the caps needs to be impact resistance throughout the mass transportation of condiment packaging.

Composition overview:

PC is a tough thermoplastic which is fully amorphous. PC is manufactured from BPA which is related to estrogenic effects at high doses. This limits the usability of this polymer as it’s not exactly chemically safe for the food packaging industry.

4. PE-LD (Polyethylene – low density)

General Properties:

Very cheap and offers good chemical and hydrolysis resistance. Also has high impact strength as low temperatures as well. The yield strength for this polymer increases with density. Also has a high tensile strength. Lower stiffness than PP and poor UV resistance so might not be a suitable choice for open transportation. The temperature for operating and heat distortion are quite low.

Composition overview:

This polymer is a semi-crystalline branched thermoplastic which is very good for injection moulding. This polymer is also chemically safe. However, due to low density, the polymer is somewhat ductile, making it harder for precise machining.

Selection matrix

Properties	Weight
Yield strength	3
Stiffness	3
Maximum service temp	2
UV resistance	4
Opaqueness	5
Sustainability	5
Density	3
Price	4

Table 3 – Weighing factors for the preform/bottle

	(Score) x (weight)			
Properties	**PET**	**PP**	**PC**	**PE-LD**
Yield strength	4x3 = 12	4x3 = 12	5x3 = 15	2x3 = 6
Stiffness	4x3 = 12	3x3 = 9	4x3 = 12	2x3 = 6
Maximum service temp	2x2 = 4	3x2 = 6	5x2 = 10	2x2 = 4
UV resistance	3x4 = 12	3x4 = 12	3x4 = 12	2x4 = 8
Opaqueness	4x5 = 20	3x5 = 15	3x5 = 15	4x5 = 20
Sustainability	5x5 = 25	5x5 = 25	1x5 = 5	5x5 = 25
Density	3x3 = 9	4x3 = 12	2x3 = 6	5x3 = 15
Price	4x4 = 16	5x4 = 20	2x4 = 8	5x4 = 20
Total	**110**	**111**	**83**	**104**

Table 4 – Material selection matrix for the preform/bottle

The results of the selection matrix deem that PP is the most suitable for a bottle, however PET is close second only behind by 1 point. The score given for PP for density and price is the reason why it outperforms PET in the selection matrix. Since the bottle needs to be opaque as well as be sustainable, PET can be chosen over PP as it essentially provides the same performance. Also, PET is suitable for both injection moulding as well as blow moulding. Since the preform is injection moulded and then later needs to be blow moulded, this makes PET a good choice for the bottle/preform.

The material choice from Granta after plotting PET compositions for the chosen material index provided the top pick to be: **PET (unfilled, semi crystalline)**

Semi crystalline means that both, ordered crystalline and disordered amorphous structures can be found in the molecular structure of the polymer. This chosen material can also be translucent/opaque which is a norm in the condiment packaging industry. Unreinforced means that it consists of only monomers and are linear which achieves good stiffness and means that the polymer is strong. This polymer is also slightly more ductile than PP homopolymer 10% talc which was chosen for the lid. This means that its easier for the condiment to be extracted from the bottle.

The chosen material is **Ertalyte PET unreinforced, semi-crystalline.** The technical data sheet is provided. Data sheet: Link

Assumptions

To determine the extreme load cases to be mechanically analysed, a few assumptions regarding the force/moment applied by an average person to open a bottle/jar cap was made. According to a study undertaken by Nottingham university in 2000, 144 subjects were tested on how much torque was required to open a jar with a lid of diameter 65mm. the results showed that the average male required 6.32 Nm and the average female required 4.51Nm. However, the more important result is that of the mean torque for a female aged 75 which was 3.04 Nm [Sheffield Halam University]. The calculations to determine the force exerted by the female over 75 is shown below and is used to determine the force exerted by a man over 75 as well as this provides the closest values to a physically impaired consumer. Since the diameter in the case study was 65mm and the diameter of the lid is 19mm, a ratio was calculated and used to determine the force required to turn the component designed for this project which is also found in the calculation below:

$$\tau = F \cdot r \rightarrow F = \frac{\tau}{r} \rightarrow F = \frac{3.04}{0.065} \rightarrow F = 46.77N \tag{1}$$

If the torque for a female over 75 is 3.04 Nm and for the average female is 4.51 Nm, the ratio is 3.04/4.51 = 0.67. Multiplying the average male torque by this ratio results in an approximate value for the torque for a male over 75 years which is 6.32*0.67 = 4.23 Nm.

Using formula (1) for the torque for males over 75 years:

$$\tau = F \cdot r \rightarrow F = \frac{\tau}{r} \rightarrow F = \frac{4.23}{0.065} \rightarrow F = 65.08N \tag{2}$$

Now using direct proportionality, calculating the force (F) for female over 75 for when the radius is 19mm:

$$F_r = \frac{F \cdot r}{old\ r} \rightarrow F_r = \frac{46.77 \cdot 0.019}{0.065} \rightarrow F = 13.67N \tag{3}$$

Using formula (3) for the force for males over 75 years:

$$F_r = \frac{F \cdot r}{old\ r} \rightarrow F_r = \frac{65.08 \cdot 0.019}{0.065} \rightarrow F = 19.02N \tag{4}$$

For simplicity during the calculations, the forces for the male and female over 75 will be averaged to avoid redundant calculations for the same movement for different genders.

$$F_{avg} = 16.34N \quad (5)$$

Mechanical Analysis

Case 1 – Check if deformation under force occurs

This case analyses the maximum force which can be applied on the lip of the cap lid to open, and in extreme case the maximum force until the slot in the groove deforms/snaps.

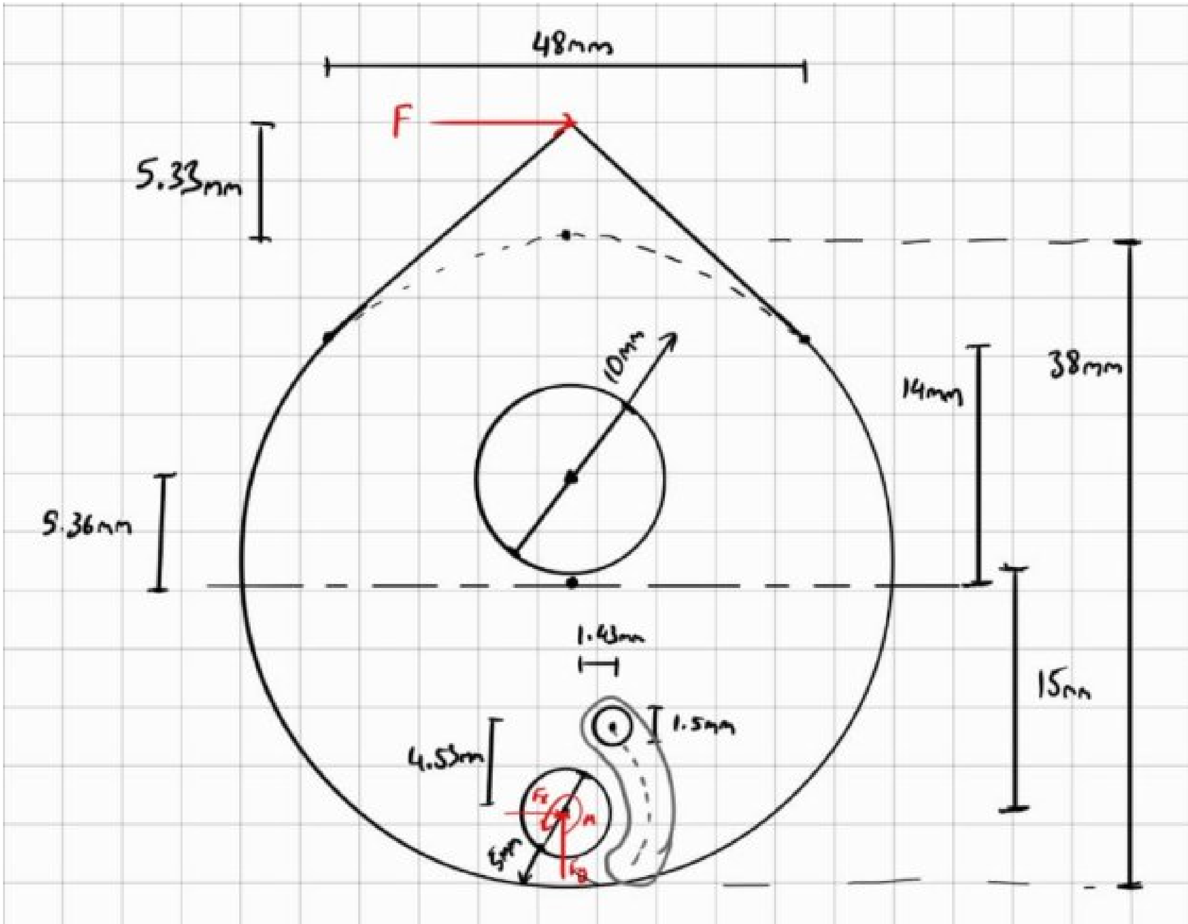
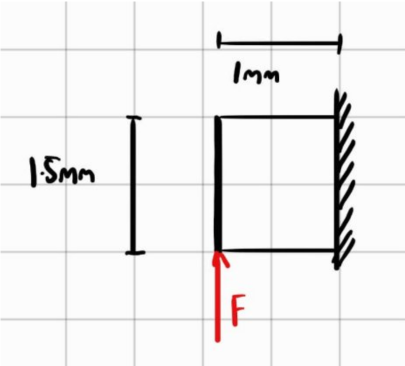


Fig 1 – Dimensioned cap lid showing force to turn the lid open

This case assumes that the force F applied at the top of the lid is the calculated force in equation (5) 16.34N. More closely, this case analyses the deformation of the cylinder in the slot/groove. This can be simplified as can be seen in Fig 2.



The formula for deflection of a beam is given by:

$$\delta = \frac{FL^3}{3EI} \quad (6)$$

The inertia for the cantilever beam is also required, which in this case is a cylinder rotating about the z axis. The inertia for a solid cylinder rotating about its z axis is given below:

$$I_{zz} = \frac{1}{12}M(3r^2 + h^2) \quad (7)$$

Where the mass (M) of the cylinder can be found through $M = \rho * V$. The density is 905kg/m^3 from the technical data sheet of the chosen material.

The full equation to determine the inertia for this cylinder is:

$$I_{zz} = \frac{1}{12}(905)(2.65x10^{-9})\ (3(0.75x10^{-3})^2 + (1.5x10^{-3})^2) \quad (8)$$

$$I_{zz} = 7.82x10^{-13}\ kg{\cdot}m^2 \quad (9)$$

The deformation (δ) can be calculated by inputting the calculated force (F) in equation (5).

$$\delta = \frac{(16.34)(0.001)^3}{3(1.5x10^9)(7.82x10^{-13})} = 4.64x10^{-6}\ m \quad (10)$$

Now calculate the max stress that acts on the cantilever beam using the equation below:

$$\sigma_{max} = \frac{3{\cdot}\delta{\cdot}E{\cdot}h}{2L^2} = \frac{3(4.64x10^{-6})(1.5x10^9)(1.5x10^{-3})}{2(0.001)^2} = 15660000\ Pa = 15.6\ MPa \quad (11)$$

Therefore, the maximum force it can sustain before deformation is 15.6 Mpa. Comparing this value to the data sheet for the chosen material, the yield strength for Polypropylene PPH 7060 homopolymer is 32 Mpa. The obtained value through calculations is below the yield strength meaning that the deformation is elastics and the cantilever beam will not undergo permanent deformation or fail. This suggests that the chosen material is suitable for its desired application.

Case 2 – Force calculations for the snap fit

The Cap is made of 2 separate components which are connected to each other by a snap fit. However, once that snap fit is engaged, its not supposed to un attach. The second snap fit is located at the hole from which the condiment can be extracted. The following section provides calculations for the snap fit force for the opening and closing snap fit on the cap.