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Reverse Engineering project of the Bialetti Moka Express coffee pot

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Executive summary

For the MICRO-301 course we were asked to “reverse engineer” an object of our choice. The goal was to try to establish a list of design specifications for the chosen product and then see how the engineers who designed the product fulfilled those specifications by analysing their final design. Our group decided to reverse engineer the Bialetti 6-cup Moka Express coffee maker. Our choice was made in part due to our love of coffee, but also because of the pot’s interesting shape and elegant working principle.

In the following report we present our findings after disassembling the product into its most basic components and analysing them individually, paying special attention to the parts that are critical for the device’s main functionality: brewing coffee. We will establish a nomenclature for the different parts constituting the coffee pot, construct a simple functional model describing the main physical principles behind the brewing of coffee in the pot and try to identify the materials used in the fabrication of each of the parts of the product as well as the manufacturing and assembling processes used. To conclude, we will perform a cost analysis of the device’s production and assembly requirements and discuss the profitability of the Moka Express, as well as developing a small critique of the design with suggestions for improvements and a life cycle assessment that analyses the sustainability and environmental impact of the manufacture and everyday use of the device.

Contents

Figure 1: Animation of the concept [1]

1 Product analysis

1.1 Functional analysis and product specifications requirements

1.1.1 Description of the product ('what')

The Bialetti Moka Express is a stove-top coffee maker. It passes boiling water through ground coffee using pressurised steam. It was originally designed by an Italian engineer called Alfonso Bialetti in 1933, named after the Yemeni city of Mocha, as a way to revolutionise making coffee at home. It has since become one of the staples of Italian culture, proudly displaying its heritage and "Designed in Italy" slogan, a country known for its innovative design and love of good coffee.

1.1.2 Targeted users ('who')

The Moka Express was designed to be used by the average kitchen user at home, with simple operation and maintenance in mind. It is quick to fill, assemble, and clean after use, taking up as little of the user's time as possible. It is also relatively cheap and does not take up a lot of storage space, producing no waste during regular operation except the depleted ground coffee. It can be easily maintained without needing any special training, through occasional cleaning of the device and replacement of critical parts, such as easily-purchasable o-rings (designed specifically for this product).

1.1.3 In which environment can it be used ('where')

The Moka Express was developed to reform the way that coffee is brewed at home, making use of existing gas or electric kitchen stoves (newer models are also compatible with induction hobs). It provides a good compromise between cost, coffee quality, operating time and ease of use. Thanks to its relatively small size and portability, it could even be used during camping trips on a gas stove, for example.

The product would not be suitable for a more professional environment, such as a café or restaurant, for two main reasons. Firstly, the device can only be used once before needing time to cool down passively, and secondly, it does not produce sufficiently high enough pressure for what is considered standard for making "proper" espresso (100 kPa to 200 kPa vs 900 kPa for traditional espresso).

1.1.4 Working principle ('how')

The Moka Express uses a simple yet elegant process to brew its coffee. The lower boiler, which is initially filled with water, is heated by an external source of heat such as a kitchen stove. This has the joint effect of heating the water in the boiler to an adequate temperature for passing through the ground coffee and subsequent consumption, as well as producing steam as a by-product.

The vast majority of generated steam, due to its much lower density and the fact that the funnel of the doser is submerged in water, is contained within the free space of the lower boiler. As more water is converted into steam, the pressure in the boiler increases, providing the driving force that will pump water at high pressure through the ground coffee placed on the lower filter disc before it accumulates in the collector.

During operation, there is a transitory phase, during which the pressure in the boiler increases to a critical point P_c, before a “steady-state” continual flow of coffee can be achieved. This can take several minutes, depending on the power and efficiency of the stove. Once the boiler reaches a critical steam pressure, there is a rapid ejection of the liquid into the collector, before a loud gurgling sound indicates that the process is complete[1].

The critical pressure P_c is determined as the pressure needed to push the liquid all way to the top of the transport tube, in addition to the pressure gradient created by the dense powder-like barrier that the ground coffee presents (see section 1.3 for more details). Once the connection to the top has been created (continuous streamline of fluid), the system becomes more or less self sustaining, requiring much less heating to maintain the critical pressure (in fact, the deposition speed becomes faster as the temperature of the water increases towards the end, resulting in a rapid ejection). When turning off the stove, it can take several seconds for the system to react, and even longer to halt the brewing process entirely.

The water pressure through the the ground coffee should be maximised to create (subjectively) better-tasting coffee, whilst accounting for safety and size considerations. For example, the lid of the container already has an internal lip to act as a “guide” for the liquid as it is ejected in an upward stream, ensuring that exiting coffee is not able to squeeze through and exit the device (the lid should not be lifted during operation!).

An animation showing key frames of the process is shown in Figure 1, from heating the boiler to driving the liquid upwards through the filter and into the collection, ready for consumption.

1.1.5 Preliminary product specifications

In order to achieve the required device functionality, the Moka Express aims to satisfy a number of criteria:

- Brew high quality coffee
- Provide sufficient coffee for 6 people ($50\,\text{mL}\,\text{person}^{-1}$)
- Be ergonomic, requiring as little storage space as possible
- Be light and easy to manipulate
- Provide a quick and easy method to brew coffee at home
- Minimise manufacture costs (reasonable end-user price)
- Ensure that the device is safe to use with no risk of injury
- Be easy to clean and require as little long-term maintenance as possible
- Good aesthetics, conforming to the classic design of the Moka Express

1.2 List of parts used in the product

The coffee pot is made up by at least 12 individual pieces[2]. The full list of the pieces can be found below.

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[1] This is due to the central tube no longer being completely occupied by fluid, allowing steam to pass and forming bubbles. While this may not be a deliberate design characteristic, it provides a useful audio cue to the operator.

[2] Certain integrated parts, such as the pressure release valve, we were unable to disassemble to inspect for ourselves, and relied on crossection diagrams available online for part analysis.

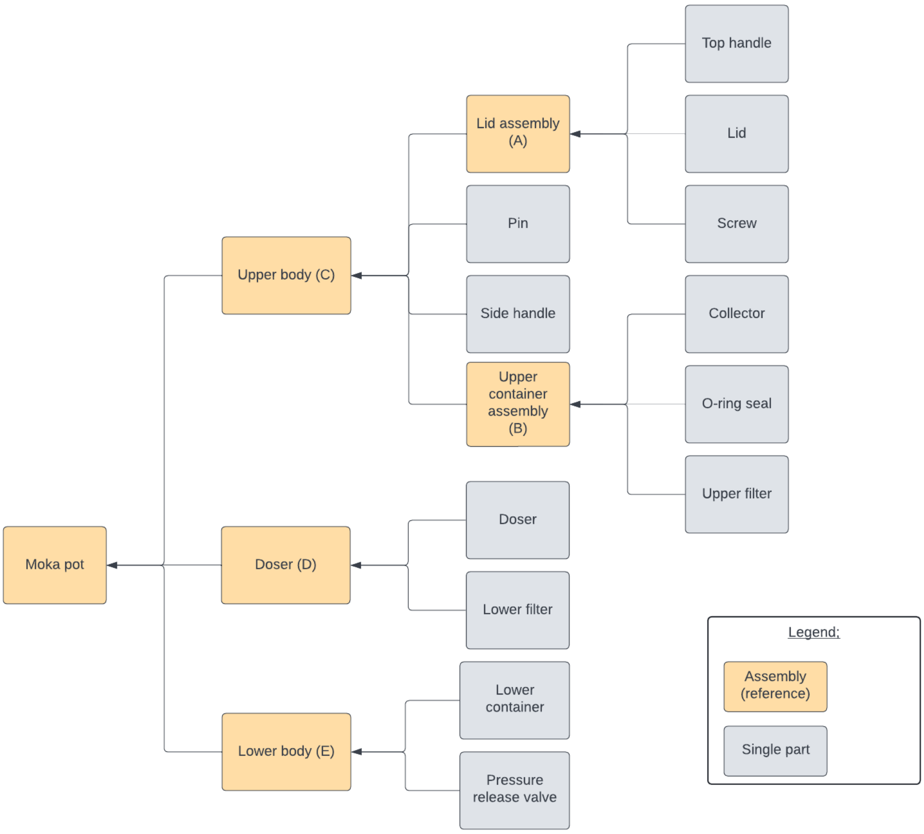

Figure 2: Tree-diagram showing the different interconnections between parts and their respective subassemblies

1.2.1 Hierarchical diagram on how parts are interconnected

The patent for the coffee pot [2] features a well established nomenclature for the different parts used by the manufacturer to describe the principle of the coffee pot. We have decided to respect this nomenclature as much as possible, with the exception of the upper container which we will refer to as the *collector*.

1.2.2 Table with the list of parts

The following table contains a description of all the parts numbered in Figure 3 constituting the Moka Express, as well as a quick summary of the identified materials and manufacturing processes. For a more in depth analysis of these last two points refer to section 2 of the report.

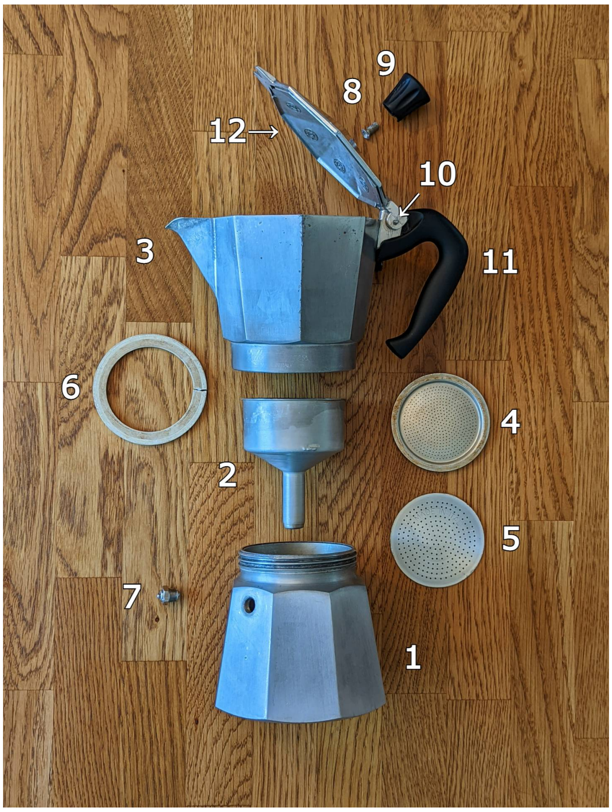

Figure 3: Exploded view of the different parts

List of object elements	
Element name	Analysis
Boiler (1)	**Description**: A large, hollow container that allows the fluid to be heated by a hot surface. It has an internal volume of 300 mL, providing sufficient brewing capacity for 6 espresso shots. Formed into a symmetrical 8-sided cone-like shape, with a drilled hole for the pressure release valve with large (non-standard) threading to allow the collector and boiler to be screwed together by hand. Forms half of the main visible body. It has a brushed surface finish for aesthetics and is easy to clean (the inside has a rough untreated surface). The bottom features circular grooves that may improve thermal conduction, or perhaps allow fluid on the hob to evacuate. **Specific function**: Heat the contained water and generate steam to provide mechanical pressure to brew the coffee. It also serves as an aesthetic element, representing half of the visible volume. **Material(s)**: The boiler is made out of a cast aluminium alloy (AlSi) which is relatively cheap and easy to manufacture and sturdy enough to contain the generated steam pressure, whilst also providing excellent thermal conductivity with the hob. It is also chemically inert with the internal fluid that will be consumed, even at high temperature. **Manufacturing process**: Appears to be a single cast piece with additional transformations (drilling and threading). **Mass**: 287 g

List of object elements	
Collector (3)	**Description**: The collector has a hexagonal shape with a height of 105 mm. It has a central transfer tube and nozzle which allows for brewed coffee to be accumulated within the collector after passing through the doser. The central cylindrical transfer tube extrusion has a depth of 70 mm and a diameter of 15 mm. At the back of the collector there is an extrusion, allowing for an interconnect with the side handle using a small metal pin. The outside surface is usually polished and for some models it can be coloured. **Specific function**: Accumulate coffee during brewing and until it is ready to be poured, provide a path for exhaust steam. **Material(s)**: The collector is made from a cast aluminium alloy (AlSi), just like the boiler. **Manufacturing process**: A single piece made by gravity die casting[3]. **Mass**: 278 g (incl. lid & side handle)
Doser (2)	**Description**: The doser is an essential part of the Moka Express, requiring specific geometry to carry out its function: The top part of the doser is a cylindrical container, and the bottom part is a conical siphon, with a long tube reaching into the boiler that is submerged in water, keeping generated steam trapped within the volume of the boiler. **Specific function**: The doser is a container made for holding the ground coffee and channelling hot water coming from the boiler to the doser chamber. The name derives from the main functionality of the piece which acts like a measuring cup for the ground coffee. **Material(s)**: The doser is made from wrought aluminium. It has a smooth surface finish and can be easily dented/deformed. It does not seem to have any additional coating or extra treatment. **Manufacturing process**: It is a single piece, likely made using deep drawing/stretching and blanking for the hole. **Mass**: 22 g
Lower filter (5)	**Description**: As the name suggests this part is a simple aluminium disk with small perforations. **Specific function**: This part keeps the ground coffee, held together through powder cohesion/friction (sand would likely pour through the holes), from falling into the boiler whilst allowing the heated water coming through the doser's tube to reach the ground coffee. The water is able to pass through the holes of the filter, it acts as a permeable floor of the ground coffee chamber. **Material(s)**: The lower filter is a small and light aluminium disk with a diameter of 60 mm and perforations which are around 1 mm in diameter, with a thickness of roughly 1 mm. **Manufacturing process**: This piece is made using simple metal sheet punching and cutting techniques. **Mass**: 5 g

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[3] Taken from a manufacturing process analysis example of a Bialetti coffee pot from the GRANTA EduPack software [3].

List of object elements	
Upper filter (4)	**Description**: This piece is very similar to the lower doser filter described above. It's a metallic disk with even smaller perforations. It's worth noting however that the upper and lower filters are not identical pieces and are therefore not made using the exact same machining process. The upper filter is thicker and has more perforations, whilst also having a slightly curved surface whereas the lower filter is completely flat. The curvature makes the piece more resistant to deformation as it's subjected to high forces as the travelling fluid pushes the dense ground coffee up against the filter. **Specific function**: It acts as a selective filter allowing only the brewed coffee liquid to pass and travel into the collector, whilst effectively blocking passage to the ground coffee that should not be present in the brewed coffee mixture. **Material(s)**: Like the lower filter, the upper filter is also made from wrought aluminium sheets. **Manufacturing process**: To shape the filter, the aluminium sheet is punched to make the holes and then deformed to create the curved surface of the filter. **Mass**: 6 g
Lid (12)	**Description**: It has a hexagonal shape, matching the collector to remain flush, with a threaded hole in the centre allowing the top handle to be fixed in place, with an extrusion that provides the interconnect with the collector using a metal pin. **Specific function**: The lid helps keep the coffee within the container as it is ejected from the nozzle, whilst also helping to keep it warm and protect against hot existing steam coming from the coffee that could injure the operator (opening the lid during/after operation is *not advised*, the coffee can be safely poured through the provided hole at the front). **Material(s)**: Made from the same aluminium alloy as the collector and the boiler. **Manufacturing process**: Like the collector, a single piece made by gravity die casting. **Mass**: *(see collector)*
Side handle (11)	**Description**: The handle has a curved shape that it shaped to be easily held. **Specific function**: Allows for the coffee pot to be manipulated after brewing to pour the coffee, as it provides good thermal insulation from the hot metal surfaces. **Material(s)**: Made from a black thermoplastic (polyolefins) that is easy to shape and has good thermal insulation. It must also be resistant to the operating temperature of the device. **Manufacturing process**: It is a single piece made using injection moulding, a cheap process with high-volume manufacturing capabilities. **Mass**: *(see collector)*
Pressure release valve (7)	*We were unable to disassemble this part with the provided tools, as it seems to have been designed to be held together by the spring from the inside (see figure 5).The pressure release value is made up of at least three individual pieces, but due to the difficulty of disassembly, we counted this as one piece.* **Description**: Ensures that excess pressure can be evacuated in case of blockage without damage to the device. It's small, circular and symmetrical in shape and can be screwed into the boiler with a standard wrench. It contains an internal spring and a rubber o-ring seal, kept closed at a certain (higher than normal) threshold force. Once this threshold is exceeded, steam is able to escape the boiler to prevent an explosion and injury to the operator. **Specific function**: Necessary safety feature to vent excess pressure from the boiler. **Material(s)**: Likely made from steel and rubber elements, surviving a rudimentary scratch test and having some significant weight to it for its small size. The strength of the steel ensures the device integrity, even after repeated activations (reusability), preventing deformation that could damage the device and render it useless as a security function. The visible surface is polished (reflective). **Mass**: 5 g

List of object elements	
O-ring seal (6)	**Description**: Creates a pressure-resistant seal between the interfaces of the metallic parts. It has a ring shape with the diameter of the "neck" of the device, with a large hole to allow the flow of liquid. It's a simple element that is hidden inside during operation and is cheap and easy (and the only part) to replace. The integrity of the seal is assured when mechanically screwing the parts together by hand with sufficient force during preparation. **Specific function**: Provide a pressure resistant seal between the metallic parts, preventing leakage of steam or liquid. Its secondary function is to be easily replaceable, and therefore cheap to manufacture and worthwhile to sell for continued use. **Material(s)**: Made from a deformable rubber-like compound, which when surfaces are contacted with sufficient pressure, provides an excellent seal for fluid and steam by deforming and matching the surface profile/roughness. It is lightweight and can be easily disposed of and replaced. **Mass**: 8 g
Top handle (9)	**Description**: An aesthetic top handle allowing for the lid to be easily opened and closed by hand. It has a symmetrical circular shape with groves to assist in grip. The piece is visible and gives the pot its unique look. **Specific function**: Provides a way to comfortably operate the lid of the device without the risk of burns, whilst providing a small aesthetic element to the device. **Material(s)**: Made from a black thermoplastic (polyolefins) that is easy to shape and has good thermal insulation. It must also be resistant to the operating temperature of the device. **Manufacturing process**: It is a single piece made using injection moulding, a cheap process with high-volume manufacturing capabilities. **Mass**: 5 g
Top handle screw (8)	**Description** : A small metallic flat-head screw. Due to loosening over time, perhaps due to thermal dilation, it needs to be tightened from time to time to keep the top handle from detaching. **Specific function**: Used to fix the top handle on top of the lid, preventing free rotation through friction. **Material(s)**: Appears to be made from a hard metal, such as steel. **Manufacturing process**: Specialised process from a mass producer. **Mass**: 1 g

1.3 Model of the main product function

The main concept behind the Moka Express is the coffee-brewing process, and therefore its ability to heat water to an adequate temperature for brewing and consumption and to generate sufficient mechanical pressure that is required to pump water through the ground coffee at adequately high pressure for brewing good-quality coffee. A simplified diagram showing the key parts of the working concept is displayed in Figure 4.

The kitchen stove is represented by a simple AC power source connected to a resistor, producing heat via the Joule effect. The heat transfer efficiency η is almost entirely dependent on the design of the hob and the thermal coupling between the two surfaces (the Moka Express base is generally smaller than most hob discs, there is also an induction variant of the Moka Express that works using a more direct heat delivery principle). The generated heat $Q = Q_1 + Q_2$ that is successfully transferred to the boiler is used for two distinct but vital functions that work in tandem[4]:

- Heating the contained water (Q_1)
- Generating steam through vaporisation (specifically, boiling) (Q_2)

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[4] The vaporisation process occurs continually at an accelerating rate as water is heated, making it difficult to estimate the

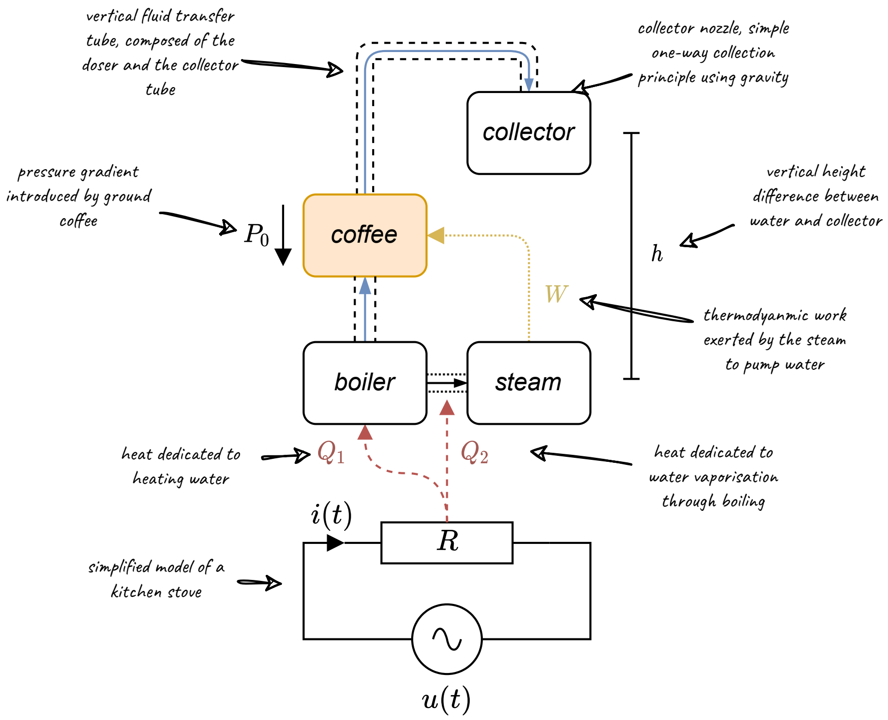

Figure 4: Simplified model of the Moka Express' main function

The fraction of heat that is used to heat the water Q_1 is determined by (1). Our efforts at analysing the process during operation suggest that the water does not reach its boiling point before a continual flow from bottom to top is achieved due to a distinct lack of sound from the lower boiler as water starts to enter the collector. Undoubtedly, water that exits the boiler towards the end will be at a higher temperature than at the start (accelerating steam generation and increasing pressure, which can be observed as the stream of exiting coffee rises higher towards the end).

$$Q_1 = m_w c_w \Delta T, \quad Q_2 = m_s L_v \tag{1}$$

At the same time that water is heated, steam is generated at an increasing rate as the water temperature rises (1). This steam generates the pressure that is required to mechanically pump water up through the system and into the coffee collector. The critical pressure to create a continuous flow of coffee can be roughly estimated as (2), where h_1 is the difference in fluid surface altitude between the boiler and the collector, and P_0 is the pressure gradient introduced by the dense ground coffee (behaving similar to a powder). It's difficult to provide an estimate for the latter, depending on the amount and type of coffee that is dispensed into the filter before use. The additional pressure generated by the resistance of the ground coffee is likely of benefit to the design as it can produce better quality[5]coffee. The amount of ideal work that the steam must exert to transfer fluid from the boiler to the collector is given by (3), where h_2 is the difference in altitude between the boiler water's centre of mass and the top of the collector nozzle (a very rough and ideal approximation, the energy needed to lift the quantity of fluid to the exit nozzle).

$$P_c = \rho g h_1 + P_0 \tag{2}$$

$$W = mgh_2 = \rho V g h_2 \tag{3}$$

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exact distribution of energy between Q_1 and Q_2. We suppose that the balance was determined empirically or by simulation to find the optimum operating point, minimising waste water/steam and brewing time whilst maximising pressure, with an additional constraint for the water temperature.

[5] Espresso coffee is made at much higher pressures than what this product can achieve (100 kPa to 200 kPa vs. 900 kPa).

We can model the mechanical process as an approximation[6] of an isobaric thermodynamic process [4]. We assume that the gas can work at constant pressure, as there is a quasi-constant flow of produced coffee at the nozzle and steam is replenished by vaporisation, but not directly heated (necessary assumptions to allow for a simple theoretical model). The exerted work can be expressed as the work done by the gas at constant pressure (4) as the gas expands to fill the boiler cavity and the central tube.

$$W = \int P_c \, dV \approx P_c \left(V_{\text{coffee}} + V_{\text{tube}}\right) \tag{4}$$

With the concepts described above, we can already establish various constraints that the designers faced during the conception of this product. Firstly, the available space in the boiler must be sufficiently small to generate high-pressure steam. An unreasonably large reservoir would waste large amounts of steam, requiring many more gas molecules to achieve the same pressure in a larger volume (van der Waals model [5]). The design also must take into consideration a maximum safe operating pressure for a dense coffee powder at maximum capacity. Although excess pressure should quickly be released as mechanical work, inadequate air volume that serves as padding may introduce unwanted hydraulic effects that could damage the device over time. As a fallback, there is also a pressure release valve in the event of a blockage.

Finally, the coffee can exit the central tube and pour into the collector, where it remains until an adequate amount of coffee has been produced. This is determined by the amount of water that can exit the boiler, due to the limited depth of the submerged doser (the funnel visible in the patent image [2]). Pumping will immediately cease once the boiler waterline descends to a certain threshold level and the central tube has cleared.

We have disregarded certain more trivial aspects of the product design that could be incorporated into the functional model, such as the thickness and material of the boiler to safely contain the pressure without damage and provide sufficient heat transfer through the air/metal/water interface (both factors are deemed negligible, as the thermal conductivity is excellent and the metal body would likely be more at risk from exterior mechanical damage from handling the device if it were any thinner).

1.4 Detailed analysis of the key elements in the product (‘part specifications’)

1.4.1 Identified key parts for the function of the system

The main purpose of the Bialetti Moka Express is brewing coffee, therefore for the functional analysis of the pot’s essential components, we will omit all of the components that do not participate in the coffee brewing process (i.e. the handles, lid and safety mechanisms such as the pressure release valve). The main components that will determine the technical specifications of the design are the boiler, the doser, the two filters, the o-ring and the collector.

1.4.2 Key elements requirements analysis

Boiler. The boiler is an essential part of the product since it’s the part that is responsible for heating the water that will later brew the coffee and generating pressurised steam for mechanical function. Another important feature of the boiler is that it has to provide a good seal so that the steam inside can build up to the required operating pressure and provide mechanical work to push the heated water up through the filters and ground coffee and into the collector. Any pressure leakage would decrease the efficiency of the device (and increase the environmental impact). From these points we can define the following specifications:

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[6] In reality, this is a real and irreversible process that would have a much lower than ideal efficiency. A deeper understanding of the physics at play would require much more complex analysis or a fluid simulation, both are beyond the scope of this report.

- It must be made with a non-toxic, non-degradable and non-oxidising material, for sanitary as well as aesthetic purposes.
- It must conduct heat well enough to boil the water.
- It must have sufficient volume to be able to make at least one cup of coffee or six espresso-sized shots as the product advertises
- It must provide a hermetic seal, this is done by forming it as one monolithic piece with minimal modifications (hole for the pressure release valve) so that there is no risk of leakage
- To satisfy the previous point, the chosen material must be easily machined/formed

Doser. This is an integral part of the device as it holds the ground coffee and also helps the operator dose the correct amount of coffee for each use with its specifically chosen volume. It also provides a channel for the heated water coming from the boiler, without letting the pressurised steam to escape, through the lower filter and the ground coffee. We can define the following specifications for the doser:

- It must be made from a material that is non-reactive with the liquid for the safety of the user consuming the brewed coffee.
- It must withstand the pressure and temperature of the heated water.

Lower filter. This piece is essential as it acts as a separator between the ground coffee, whilst still remaining permeable to heated water that is pumped from below. It must satisfy the following criteria:

- As with all the pieces that come in contact with the coffee, the lower filter must be made with a material that can safely come into contact with heated water and coffee without producing any toxic byproducts or substances that might be a health risk if consumed (rust, plastic particles, ...).
- The filter holes must have the right size to prevent the dry compacted coffee from falling into the boiler while guaranteeing the passage of heated water.
- The filter must be able to withstand the pressure of the pumped water and temperature of the heated water.

Upper filter. This filter allows the brewed coffee to pass into the collector whilst remaining impermeable to ground coffee, even when forced against the filter with significant force. It must fill the same criteria as the lower filter, whilst being able to withstand additional pressure (due to the fact that the coffee generates a significant pressure gradient, therefore generating a large force that is applied to the surface of the upper filter). This is why the upper piece is curved and features perforations with a smaller diameter compared to the lower filter.

O-ring. This piece acts as a gasket, preventing any steam or brewed coffee from leaking between the collector and the doser. It must be able to provide adequate sealing against liquid and gas at the operating pressure of the device. The boiler and doser are shaped in such a way that they are both in contact with the o-ring surface, effectively providing a three-part seal between the boiler, doser and collector. This piece is mounted on the bottom of the collector, and the seal is created by the operator's mechanical strength (by hand) before each use when the parts boiler and collector are screwed together. The specifications for this piece are:

- It acts as a gasket so it should be made with a flexible material such as an elastomer that can deform and provide adequate sealing between the boiler, doser and collector.

- The elastomer picked should be able to withstand the high temperature of the heated water.
- It must be able to withstand the required mechanical stress and not damage under shearing forces.
- It should be able to withstand as many re-uses as possible, and easy to manufacture and distribute for maintenance.

Collector. This piece has the sole purpose of collecting the brewed coffee (and providing one of the main aesthetic elements). There is a long tube in the centre that allows the brewed coffee to travel from the doser up to the collector via a nozzle to be accumulated. The specifications for this piece are:

- It must be able to accumulate the entirety of the boiler's water capacity (6 espresso-sized shots).
- If possible, insulate the brewed coffee so that it remains as hot as possible for consumption (secondary concern).
- This piece is a visible piece so it must be made with a material and finish that is aesthetically pleasing (polished metal).
- As with all the other pieces, the material should be non-reactive and safe to store consumable substances in.

2 Implementation (3 pts)

2.1 Process used for the main elements identified in Part I

2.1.1 Material identification

The product is made from five distinct materials, wrought aluminium, an aluminium alloy (AlSi), an opaque thermoplastic (polyolefin), steel and an elastomer.

As mentioned in the part table in section 1.2.2, the main body is made of a cast aluminium alloy (passes the magnetisation test). It's not the cheapest material and does not have the highest strength, but still provides an adequate balance between cost and strength whilst being applicable for coffee-brewing purposes and remaining sufficiently reusable after end-of-life. Metal also has the quality of having high thermal conductivity, as opposed to ceramics for example, is not oxidising and is about 8-10 times cheaper than stainless steel. Aluminium is also a lot easier to work and shape than steel.

After checking that the doser is not ferromagnetic (test with a hard magnet) and seeing that it is a very thin, light and deformable (even in the hand), we conclude that it was also made using (likely pure) wrought aluminium. A similar analysis of the two filters yielded the same result.

The two plastic parts (side handle handle and lid handle), although not essential to satisfy the main functionality of the Moka Express, are still important additions to the product as they provide a handling safety aspect. These pieces were most probably made using the same material to simplify inventory (the material also looks identical). They must be able to support the operating temperature of the device without melting or deforming, they don't need to withstand any sort of elevated pressure and are opaque, therefore likely semi-crystalline. There is a likely plastics group candidate called *polyolefins* that matches our description. To determine more accurately the type of plastic used, we performed the polymer identification test and discovered that these pieces were likely made using PE, which belongs to the polyolefins plastics group, agreeing with our initial classification.

The o-ring is made of an elastomer. After testing we determined that it is likely a silicon-based elastomer. This is again a very reasonable choice, as silicon is often used to make gaskets in kitchen appliances, cookware and food storage containers. It provides good steam and chemical resistance with a low compression set [6] .

2.1.2 Collector

The boiler, collector and lid were likely made using a type of metal casting manufacturing process. The boiler has a shape that would be very difficult to imprint with a piston, and the collector has a more complex geometrical shape, as well as a tell-tale parting line that is inherent to casting techniques. Ergo the necessary casting manufacturing technique of this part justifies the choice of cast aluminium alloy as a material, since the latter is commonly used in gravity die casting processes and in kitchen appliances in part thanks to the material's good resistance to corrosion, good thermal conductivity and low heat expansion coefficient [3].

2.1.3 Boiler

The four little points on the bottom of the collector are likely supports to stop the upper filter from deforming at high pressure. These supports would be difficult to machine using classical techniques which keeps hinting at a casting manufacturing process for this part. This part also features undecipherable markings on the underside that are likely related to internal tools and manufacturing processes, perhaps the date or machine identifiers. These markings are extruding from the lid and the collectors which is yet

Figure 5: Section view of the pressure release valve.

another hint that these pieces were likely cast (as they are an extrusion and not stamped). Both upper and lower parts have an outside brushed surface finish.

2.1.4 Doser

The doser was most likely made with a stamping process as it does not bear any sign of a casting procedure. It would be fairly easy to make starting with a sheet of wrought aluminium and stamping it into the doser shape. Then the tip of the cone would be cut to open the bottom of the doser. Finally, it seems the piece got an outside finish since it has a shiny appearance with typical sanding/brushed look.

2.1.5 Upper and lower filters

The filters were also most probably made using a die piercing process from sheet metal. They also seem to be made using pure aluminium.

2.1.6 Other parts

Pressure valve

This is a complicated piece to manufacture , likely made by an external supplier that specialises in the fabrication of the part due to its general-purpose and monolithic design. The internal assembly is difficult to ascertain, given our inability to disassemble the piece with the tools at hand. From our online cross-analysis, it seems to contain at least two rigid steel pieces, held together by a spring in a sort of piston action with a rubber o-ring to improve the seal (see Figure 5). The pressure valve as a whole can be screwed into the boiler with an standard wrench.

O-ring

There are many different ways to manufacture rubber gaskets, ranging from die cutting to injection moulding. It would seem the piece used in the coffee pot was made with some sort of die cutting process just by verifying that there are no parting lines on the gasket. Also the gasket has a very simple geometry so it would be fair to say that a mould is not necessary.

Handles

The plastic handles were most likely made using an injection mould process, as they both have a complex shape and we can clearly see parting lines on both pieces. The top handle is fixed to the top lid using a metal screw that passes through a circular hole in the lid in a three-part assembly. The assembly is not very robust, the plastic threading can weaken over time, resulting in some play and free rotation of the top handle.

Screw

The screw is of a standard size and likely bought from a mass-producing manufacturer due to cost and complexity of in-house production.

2.2 Assembly sequence

The assembly sequence and hierarchical relationships between the different parts are illustrated in Figure 2. We can observe that the Moka Express can be separated into three main parts: the upper body (sub-assembly C), the doser assembly (sub-assembly D) and the lower body (sub-assembly E). The Moka Express is relatively easy to assemble as the whole process can be done by hand with the a help of a few standard tools (screw driver, hammer, pin pusher and wrench). To assemble the upper body, we must first screw the lid handle on the lid of the pot using a screwdriver. Then the assembled lid and the side handle are connected to the collector via a pin. The upper filter and the o-ring are then inserted into the bottom of the collector without the help of any fastening pieces, the tightening of the lower body to the upper body will later hold the gasket and the upper filter in place. For the doser assembly, the lower filter is inserted into the doser then a couple of indentations are made into the doser's body to secure the filter in its place. Finally, to assemble the lower body of the pot, the pressure release valve is screwed on the boiler using a wrench. Now that the three main pieces are assembled, the doser assembly can be inserted into the lower body by hand (during preparation of the device) and then secured in place by aligning the upper and lower bodies and screwing them together to finish the assembly.

Using (5) we can estimate the cost of manual assembly of the product. This estimation takes into account the time loss due to the difficulty of handling H and fitting F of the different components of our product as well as the labour cost C_L[7] .

$$C_{ma} = C_L(F + H) \tag{5}$$

Due to the simplicity of the assembly of the Moka Express, the largest time penalties were due to the screwing of different components and sub-assemblies as well as the use of small tools (for tightening, placing the pin and making the indentations in the doser).

We estimated a cost of assembly of 0.776 CHF. A table containing a detailed cost analysis is available in Figure 10 in the Annex.

2.3 Cost analysis

The cost of manufacturing C of a product can be estimated using the equation shown in Figure 6. Using the GRANTA EduPack software [3] we were able to estimate the cost of materials as well as the tooling and equipment costs for the different materials and manufacturing processes identified in section 2. Assuming a capital write off time of 10 years for all the pieces and an overhead rate of $40\,\mathrm{CHF\,h^{-1}}$ we estimate a total cost of around 14.574 CHF for the manufacturing/procurement of all the necessary parts for the Moka Express. Note that in our analysis we assumed that the pressure release valves, the screws and the pins were all bought from their respective specialised vendors. A detailed table in the annex shows the different costs of each piece as well as more details about the assumptions made for the cost estimation (Figure 11). We do not take into account any additional manufacturing processes such as the polishing and threading of the boiler and collector nor do we take into account packaging and labelling

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[7] All costs will be in CHF, C_L is the labour cost in Switzerland during 2022.

$$C = \overset{\text{Material cost}}{\boxed{\left(\frac{m}{1-f}\right)C_{rm}}} + \overset{\text{Gross overhead}}{\boxed{\frac{1}{\dot{n}}\left[\left(\frac{1}{L}\right)\frac{C_c}{t_{wo}}+\dot{C}_{oh}\right]}} + \overset{\text{Dedicated cost}}{\boxed{\left(\frac{C_t}{n}\right)\left\{1+E\left(\frac{n}{n_t}\right)\right\}}}$$

Figure 6: Production cost of a part where m is the mass of the part, f the fraction of lost material, $\dot{n}$ is the unit production rate, L is the equipment load per day, t_{wo} is the capital write-off time, C_c the equipment cost, $\dot{C}_{oh}$ is the overhead rate, n is the number of parts to be produced, C_t the tooling cost and $E(\frac{n}{n_t})$ the integer division of n by n_t where n_t is the tool lifetime in number of units produced.

costs. These could further increase the accuracy of our manufacturing cost estimation, but likely do not provide a significant influence considering the uncertainty of our values.

Finally we can estimate the total cost of manufacturing and assembly of the Moka Express to be around 15.35 CHF. Knowing that the retail price of the 6-cup variant pot is around 29.70 CHF[8], we estimate the overall profit made between the manufacturer and the retailer to be in the region of 14.35 CHF[9] or around a 48% profit margin.

It's worth noting that, like with capsule or cartridge based appliances, Bialetti likely aims to make further profit from selling replacement o-rings. A packet of four costs 1.95 CHF (best deal at −41 %). Bialetti advises replacing the o-ring every 3 to 12 months. Assuming that the ring is changed every 4 months, over a 10 year lifespan this equates to a cost of 60 CHF, with only packaging and distribution costs being of significance. Even buying just a single replacement at 3.30 CHF twice a year for five years costs 33 CHF, which is still twice the estimated profit margin of a single Bialetti Moka Express.

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[8] Taken from the Digitec Galaxus AG website (2022-06-05).

[9] This does not include distribution and administration costs after fabrication directly, although they are somewhat compensated by our overhead cost estimation.

3 Critical analysis / Variants (2 pts)

3.1 Weak points in the design, possible source of failure

The design of the Moka Express, whilst being very elegant and fulfilling all of the required specifications, still has some weak points.

For example the Moka Express that we analysed is not compatible for use with an induction cook top[10]which is starting to become more and more commonplace, meaning this model is essentially becoming obsolete and must be replaced. Also, the collector is not a very good thermal insulator and does not keep the coffee warm for long (minor concern). There are certain safety considerations around the design of the product: seeing as the coffee pot is tall and narrow compared to most other pots and pans, it is prone to being knocked over, spilling hot coffee and releasing steam, leading to possible injury to anyone near the device. Another issue is the accidental opening of the lid during operation, with no visible printed warning on the device, this could lead to scalding or even burns for the operator from hot steam or even sputtering coffee. Also in the case of the device toppling there is a risk of damaging the side handle seeing as it is a long extruding piece connected only on one side by a single pin, this would render the device practically unusable since this piece is almost impossible to replace without a DIY solution, further increasing the risk of use to the operator (the product has no concern for repairability, given the relatively low cost).

Furthermore, the Moka Express cannot be cleaned in a dishwasher and should not be descaled with citric acid as this may react with the aluminium body and pose a health risk to the consumer. Therefore the pot has to be washed manually, this however cannot be done immediately after use since the pot has to cool down after each use before it can be used again or even cleaned. The throughput of coffee is therefore low compared to other coffee brewing methods. In regards to portability, especially in a travel context, the design could be improved: because of its non regular shape it is not optimal for backpacking for example, and can't be folded together or reduced in size (a lot of wasted volume).

3.2 Suggestion of possible improvements and corrective actions

The use of stainless steel is a possible improvement since it is compatible with an induction hob and can be washed very easily as it doesn't have the same drawbacks as the aluminium, however it would be harder and more costly to shape the stainless steel since it's more expensive than the cast aluminium alloys ($2.75\,\mathrm{CHF\,kg^{-1}}$ vs. $1.98\,\mathrm{CHF\,kg^{-1}}$ and has a higher melting point, around 1400 °C vs. 600 °C [3]). A more circular shape could be interesting as it could fit easier in some packing spaces unlike the octagonal shape. A more robust interconnect between the side handle and the collector could improve the durability and longevity of the product. This would, of course, increase the manufacturing and assembly cost of the product, this modification however will probably not be enough to raise the retail price of the pot in order to remain at a rounded and well-placed price point, resulting in a reduction in profits, and is therefore unlikely to happen. The decision of the designers to not add the second connection point constitutes a good example of DFM (*Design For Manufacturing*) and DFA (*Design For Assembly*). A more secure lid or even a printed warning, even if this goes against the elegant asthetic that Bialetti is striving to achieve, or even adding a simple locking mechanism, in the (hopefully) very unlikely case that a child may interfere or get curious during the brewing process, could result in fewer burns and therefore injuries from product misuse.

Figure 7: View of an Nespresso coffee machine

3.3 Comparison with other design variants fulfilling completely or partially the same set of specifications

There is a large and competitive market of products specialised in brewing coffee or any other hot beverages. One such well-known brand for example is the Nespresso coffee machine and capsule ecosystem. One major advantage of this coffee machine is its convenience materialised by the possibility to use single-cup portions (with each capsule containing enough coffee for one cup) and wide variety of advertised flavours, this makes it very simple and easy to use as the user only pops a capsule into the machine and presses a button. Also, there is no need to wash the Nespresso machine as regularly as the Moka Express, but it needs to be descaled every 6 to 12 months. In comparison, the Moka Express needs to be washed after every use. Its design is very modern as well and since the coffee is made without any human interaction, the quality and taste of the coffee brews will be consistent between uses. Another advantage of the Nespresso machine, that Bialetti will likely struggle to compete in due to the capsule-less technology, is the variety of the available drinks: there are many beverages one could make with a Nespresso machine including cappuccinos, lungos or even tea and hot chocolate. One could even make cold beverages with a Nespresso machine, unlike the Moka Express with is just limited to hot coffee and water based drinks (no cream or milk, these must be added to the beverage after brewing, also making the creamy brew of the Nespresso machines look is more advanced). Finally with a Nespresso machine the throughput of coffee is higher than with a Moka Express since there is no need to wait for the machine to cool down or to empty it before reusing.

In terms of disadvantages, a Nespresso machine is more expensive as it costs around 100 CHF, the user also has no choice but to use the capsules provided by the supplier, which make them obliged to buy from the same vendor, or risk using third-party capsules that may not have Nespresso's guarantee. Additionally, not all capsules are compatible with all Nespresso machines, introducing additional complexity to the end user. Finally the device is much bigger and heavier and requires a larger space to store. It is not a portable device therefore it cannot be taken on a camping trip for example.

There are of course many other ways of preparing coffee each one with its own advantages and disadvantages, Nespresso is one of the big contenders in brewing good quality coffee compared to simpler and more traditional methods, but overall the main advantages of the Moka Express is its portability, size, and last but not least, its aesthetic *Italian* appeal. It is lacking, however, in the diversity of drinks it can produce and in speed and throughput.

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[10] Newer models are compatible with induction stoves, offering better efficiency and possibly faster brewing times.

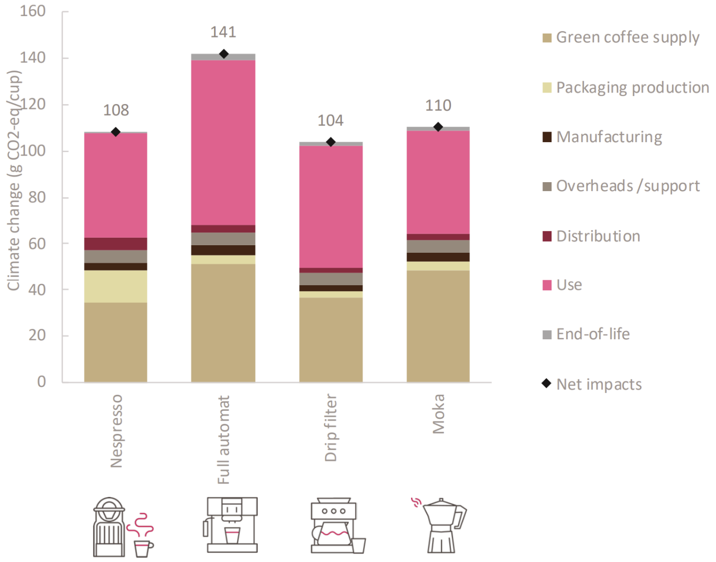

Figure 8: Quantis' life cycle analysis of different coffee brewing methods [7]

4 Essay on sustainability analysis

We found it compelling and contemporary to develop this section on the sustainability of brewing coffee, given its widespread everyday use and environmental impact, as an optional addition to the structural requirements provided to us for this project.

4.1 Product life cycle

The product life cycle of the Moka Express can be split into two major subcategories, the life cycle of the product itself (number of cups produced, maintainability, ...) and the environmental impact of the coffee brewing process itself compared to other means, such as a capsule-based machine or a filter coffee machine.

The life-cycle of the product itself can be split into different stages, extract and transformation, assembly, distribution, use and resource consumption and disposal. The body is made almost exclusively out of aluminium and plastic. Both of these materials have the potential to be sourced from sustainable/recycled sources, Bialetti's website indicates that the product is made entirely from recycled aluminium [8]. The manufacture of the product itself involves various metal forming and plastic injection techniques and is carried out in Romania, which is situated roughly 1000 km from the design origin, Italy. The assembly itself is trivial and negligible compared to other factors (see section 2.2). Regional exports to Europe can be carried out by heavy-duty trucks, whilst worldwide exports can be loaded onto container ships on the adjacent Black Sea for international shipping. Once the product has reached the end-user, it can be reused a large number of times due to its simplicity and excellent maintainability (but not repairability). Brewing a cup of coffee a day, we estimate that this product can easily achieve a lifespan of 5+ years[11] (author's experience) if kept in good working order. Maintenance consists of buying replacement rubber o-rings (every 3 to 12 months, depending on usage), which itself incurs an environmental cost due to the manufacture, transport and commerce of small elements with large paper/plastic packaging. As the product reaches its end of life, it can either be kept as a decorative element in homes thanks to its aesthetic design or recycled. The aluminium body itself has very high recyclability, the plastic and rubber elements must likely be disposed of as waste.

The lifecycle analysis of a coffee maker must also take into account the effect of regularly brewing coffee with the product and its unique design, compared to other solutions such as capsule-based coffee ma-

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[11] Bialetti claims an average lifespan of 10 years with minimum maintenance requirements.

Brewing technology	CO_2 per cup [g]
Drip coffee maker	436.92
Moka pot	204.81
French press	176.69
Stovetop maker	160.19

Table 2: Energy consumption of different coffee brewing methods according to an MIT article [9]

chines or traditional press makers. This is likely to be the biggest contributing factor to the product's environmental impact over its lifespan. Here, we get slight variations from different sources. A study from Quantis [7], commissioned by Nespresso, found that drip coffee makers had the lowest impact (by an almost negligible fraction), while the Moka Express was only slightly worse than the Nespresso ecosystem since it requires more ground coffee for a single cup (see Figure 8). The gain that Nespresso achieves in its coffee supply efficiency is almost entirely offset by the impact of its non-negligible packaging and distribution requirements. An article from MIT's Office of Sustainability [9] shows that from traditional non-capsule methods, the Moka Express has the smallest carbon footprint per-cup-brewed. This trend is further supported by CET [10], ranking the Moka Express as the least impactful compared to capsule-based and fully automated coffee machines. In conclusion, the majority of the carbon impact from the coffee brewing process for the Moka Express is the result of direct energy use and ground coffee sourcing (85.4 % according to the Quantis analysis), which in turn depend largely on how the consumer can offset these requirements (green energy, ethically sourced coffee).

4.2 Sustainability assessment of the product

When compared to more traditional coffee-brewing approaches, such as drip coffee markers, the Moka Express has one of the lowest carbon emission impacts per cup of coffee brewed. The environmental impact of the manufacture of a coffee machine itself is relatively minor when compared to the energy and coffee sourcing requirements duing the use of the product. The Moka Express does not produce any excess waste other than the the bio-degradable and compostable depleted ground coffee, not requiring any special recycling schemes such as those offered by Nespresso vendors. The product does not require any chemical detergents for cleaning (such as descalers for automated coffee machines), a simple rinse with hot water after use is enough. Furthermore, it is a relatively green investment as it is high-quality and robust product that can last at least 10 years when kept in good condition, with no fragile parts that could render the device non-functional after only a short period (as has become the norm with a lot of low-cost electronics), and can be recycled after its end-of-life.

Regarding the contemporary carbon footprint of brewing coffee, the production of one 40 mL coffee cup with the induction variant of the Moka Express releases as little as 8 g of CO_2e [10], these emissions can be as low as 18 % or 56 % lower than those resulting from the use of a coffee capsule (10 g CO_2e) or coffee pod (18.5 g CO_2e) coffee machines. Therefore, the use of ground coffee with the Moka Express could save as much as much as 10.3 g or 1.8 g of CO_2e for a single cup of coffee.

5 Conclusion

Through our extensive analysis of the Moka Express, we have tried to understand the choices made by the designers of the Bialetti Moka Express to satisfy the design specifications that we judged necessary for such a coffee-brewing device. We have observed how the Bialetti Moka Express engineers were able to design a practical, easy-to-use and long-lasting product for a very reasonable price for the consumer in a competitive market. Making use of a clever and time-tested coffee brewing technique, the Moka Express can make high quality-coffee repeatedly (as long as the user is able to source high-quality coffee to use with the device) requiring little to no maintenance or upkeep. By using materials such as cast aluminium alloys and polyolefin plastics, the designers were able to create an aesthetically appealing look for the pot without infringing on the device's functionality, all the while optimising it for lowering manufacturing and assembly costs for an acceptable profit margin. Finally, whilst not being the most environmentally friendly method of brewing coffee (according to some sources), the Moka Express can still hold its own against the market leaders and can be considered as one of the cleanest, most durable and cheapest ways of making this intoxicating nectar that is coffee.

6 Annex

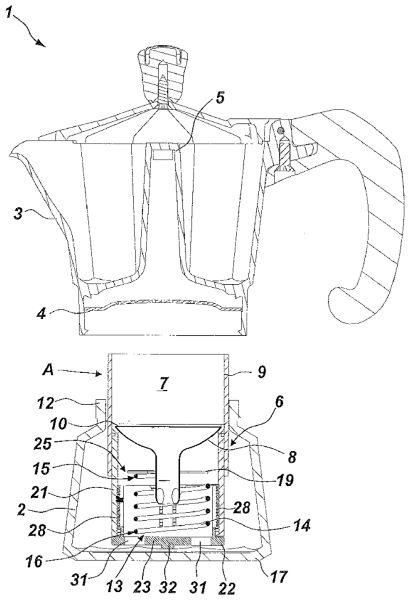
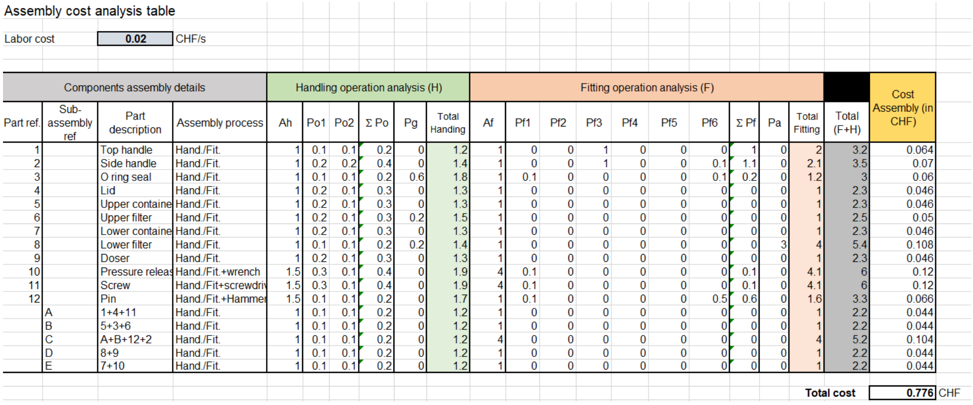


Figure 9: Image from the patent of a Bialetti Moka Express [2]



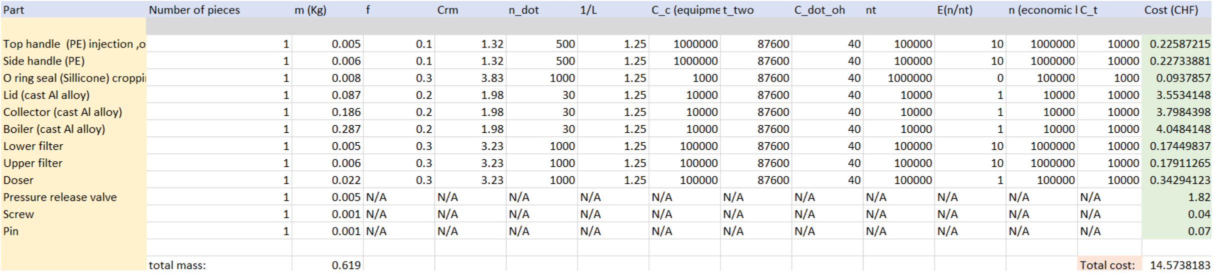
Assembly cost analysis table

Labor cost 0.02 CHF/s

Components assembly details				Handling operation analysis (H)						Fitting operation analysis (F)												Cost Assembly (in CHF)
Part ref.	Sub-assembly ref	Part description	Assembly process	Ah	Po1	Po2	Σ Po	Pg	Total Handing	Af	Pf1	Pf2	Pf3	Pf4	Pf5	Pf6	Σ Pf	Pa	Total Fitting	Total (F+H)	
1		Top handle	Hand./Fit.	1	0.1	0.1	0.2	0	1.2	1	0	0	1	0	0	0	1	0	2	3.2	0.064
2		Side handle	Hand./Fit.	1	0.2	0.2	0.4	0	1.4	1	0	0	1	0	0	0.1	1.1	0	2.1	3.5	0.07
3		O ring seal	Hand./Fit.	1	0.1	0.1	0.2	0.6	1.8	1	0.1	0	0	0	0	0.1	0.2	0	1.2	3	0.06
4		Lid	Hand./Fit.	1	0.2	0.1	0.3	0	1.3	1	0	0	0	0	0	0	0	0	1	2.3	0.046
5		Upper containe	Hand./Fit.	1	0.2	0.1	0.3	0	1.3	1	0	0	0	0	0	0	0	0	1	2.3	0.046
6		Upper filter	Hand./Fit.	1	0.2	0.1	0.3	0.2	1.5	1	0	0	0	0	0	0	0	0	1	2.5	0.05
7		Lower containe	Hand./Fit.	1	0.2	0.1	0.3	0	1.3	1	0	0	0	0	0	0	0	0	1	2.3	0.046
8		Lower filter	Hand./Fit.	1	0.1	0.1	0.2	0.2	1.4	1	0	0	0	0	0	0	0	3	4	5.4	0.108
9		Doser	Hand./Fit.	1	0.2	0.1	0.3	0	1.3	1	0	0	0	0	0	0	0	0	1	2.3	0.046
10		Pressure releas	Hand./Fit.+wrench	1.5	0.3	0.1	0.4	0	1.9	4	0.1	0	0	0	0	0	0.1	0	4.1	6	0.12
11		Screw	Hand./Fit+screwdriv	1.5	0.3	0.1	0.4	0	1.9	4	0.1	0	0	0	0	0	0.1	0	4.1	6	0.12
12		Pin	Hand./Fit.+Hammer	1.5	0.1	0.1	0.2	0	1.7	1	0.1	0	0	0	0	0.5	0.6	0	1.6	3.3	0.066
	A	1+4+11	Hand./Fit.	1	0.1	0.1	0.2	0	1.2	1	0	0	0	0	0	0	0	0	1	2.2	0.044
	B	5+3+6	Hand./Fit.	1	0.1	0.1	0.2	0	1.2	1	0	0	0	0	0	0	0	0	1	2.2	0.044
	C	A+B+12+2	Hand./Fit.	1	0.1	0.1	0.2	0	1.2	4	0	0	0	0	0	0	0	0	4	5.2	0.104
	D	8+9	Hand./Fit.	1	0.1	0.1	0.2	0	1.2	1	0	0	0	0	0	0	0	0	1	2.2	0.044
	E	7+10	Hand./Fit.	1	0.1	0.1	0.2	0	1.2	1	0	0	0	0	0	0	0	0	1	2.2	0.044

Total cost 0.776 CHF

Figure 10: Assembly of a Moka Express cost analysis table



Part	Number of pieces	m (Kg)	f	Crm	n_dot	1/L	C_c (equipme	t_two	C_dot_oh	nt	E(n/nt)	n (economic l	C_t	Cost (CHF)
Top handle (PE) injection ,o	1	0.005	0.1	1.32	500	1.25	1000000	87600	40	100000	10	1000000	10000	0.22587215
Side handle (PE)	1	0.006	0.1	1.32	500	1.25	1000000	87600	40	100000	10	1000000	10000	0.22733881
O ring seal (Sillicone) croppi	1	0.008	0.3	3.83	1000	1.25	1000	87600	40	1000000	0	100000	1000	0.0937857
Lid (cast Al alloy)	1	0.087	0.2	1.98	30	1.25	10000	87600	40	10000	1	10000	10000	3.5534148
Collector (cast Al alloy)	1	0.186	0.2	1.98	30	1.25	10000	87600	40	10000	1	10000	10000	3.7984398
Boiler (cast Al alloy)	1	0.287	0.2	1.98	30	1.25	10000	87600	40	10000	1	10000	10000	4.0484148
Lower filter	1	0.005	0.3	3.23	1000	1.25	100000	87600	40	100000	10	1000000	10000	0.17449837
Upper filter	1	0.006	0.3	3.23	1000	1.25	100000	87600	40	100000	10	1000000	10000	0.17911265
Doser	1	0.022	0.3	3.23	1000	1.25	100000	87600	40	100000	1	100000	10000	0.34294123
Pressure release valve	1	0.005	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.82
Screw	1	0.001	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.04
Pin	1	0.001	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.07
	total mass:	0.619											Total cost:	14.5738183

Figure 11: cost estimation of the different parts of a 6-cup Moka Express. The retail price of the pressure release valve is 2.60 CHF [11], if we assume a 30 % price reduction for bulk purchasing directly from the manufacturer the price becomes 1.82 CHF. The screws [12] and pins [13] were also assumed to be bought in bulk quantity from a specialised manufacturer. Note that these pieces are not the exact ones bought by the Bialetti manufacturer but they provide a good cost approximation. Finally, the masses of the lid, side handle and pin were assumed to be a third of the overall measured mass of the collector, side handle, lid and pin assembly which we were unable to disassemble.

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[13] **Parallel Pin (1-1000 pieces per package)**. URL: `https://uk.misumi-ec.com/vona2/detail/221005016322/`.