Final Design Report

ME40228: Group Business Design Project – Group 6

21st March 2021

Summary

This final design report explores each part of the design for an electric DC kettle as well as the whole appliance. The project brief set out by Efficiency for Access and Engineers Without Borders for the design challenge highlights the importance of designing super-efficient DC appliances for those who are lagging furthest behind on achieving the UN Sustainable Development Goals. In the earlier stages of this project, the group decided to design a kettle which provides a positive social impact by efficiently boiling water for drinking, cooking, washing and cleaning. The design of each sub-system was carefully considered with the target user in mind as well as commercial viability. Employing a number of techniques to ensure that the kettle will bring a positive social impact; technical analysis, prototyping, experiments, reverse engineering and iterative design were all used. The final design is embodied as an insulated filtering kettle with dual boiling modes. This allows for savings in energy when the kettle is only being used to heat water to kill viruses and bacteria. The insulation keeps water warmer for longer as well as improving efficiency while heating. Filtering makes sure that not only bacteria and viruses are killed but other contaminants are as well. As well as each technical area, there is a report on the management and design process throughout this project.

Contents

List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
BoM	Bill of Materials
CE	European Conformity
DFMEA	Design Failure Mode and Effects Analysis
EfA	Efficiency for Access
EWB	Engineer Without Borders
HoQ	House of Quality
IEA	International Energy Agency
PDS	Product Design Specification
PM	Project Management
QA	Quality Assurance
RoHS	Restriction of Hazardous Substances
SDG	Sustainable Development Goals

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1 Project Introduction, Integration and Management

1.1 Introduction

1.1.1 Context

The UN SDG 7 identifies access to reliable, affordable, and modern energy as a critical step in eliminating poverty around the world. Access to energy is an enabler and central to achieving many of the other SDGs [1].

The most economical way of achieving electrification in remote and peri-urban settings is through DC mini-grids[1] and solar home systems. With the turn of the decade, access to energy in developing regions is growing. The IEA forecasts more than 600 million people in Sub-Saharan Africa need to be served by an off-grid renewable solution by 2030 to meet SDG 7 [2].

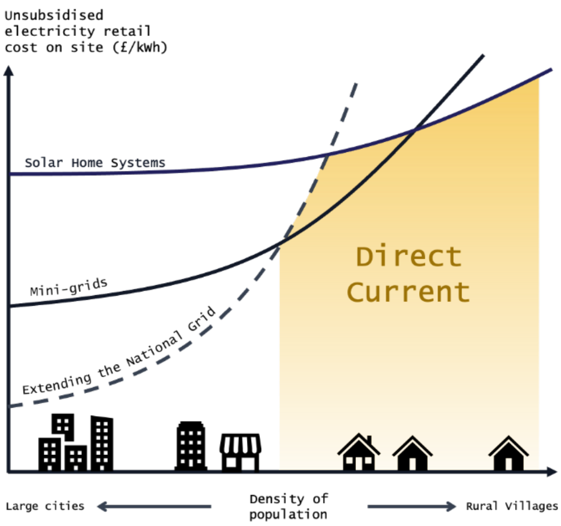


Figure 1: As population density decreases, solar home systems and mini grids become the most affordable way of providing electricity top homes

Conventional, inefficient appliances use far too much energy to be used affordably with off-grid solar home systems or mini-grids. The burden of inefficient appliances can overload these small systems causing load shedding and outages.

In conjunction with EWB, the EfA design challenge sets out the task of designing an efficient appliance to fill this need for the global developing population. This project is to design a super-

[1] Mini-grids are small scale off-grid electricity generation and distribution networks, typically less than 10kW. They often supply a localised group of customers in a small town or village.

efficient DC appliance that works towards the goals of positive social impact, helping those lagging furthest behind on achieving the SDGs.

1.1.2 Problem Statement

The need for boiling water for drinking and cooking has previously been identified, as well as the benefits boiling can have in killing harmful bacteria found in contaminated water [3] [4]. 2.2 billion people lack access to safe drinking water with 1000 children dying every day from diarrhoea alone. Treating household water would help solve this problem.

Many of the areas around the world which suffer from poor access to clean water also suffer from poor access to electricity. The region with lowest rates of access is Sub-Saharan Africa; growth in this sector is occurring, with localised regions such as Kenya seeing huge growth in electrification. In 2020, 80% of off-grid solar appliance sales in East Africa, were in Kenya making it an ideal location to market and design a DC electrical appliance for [5].

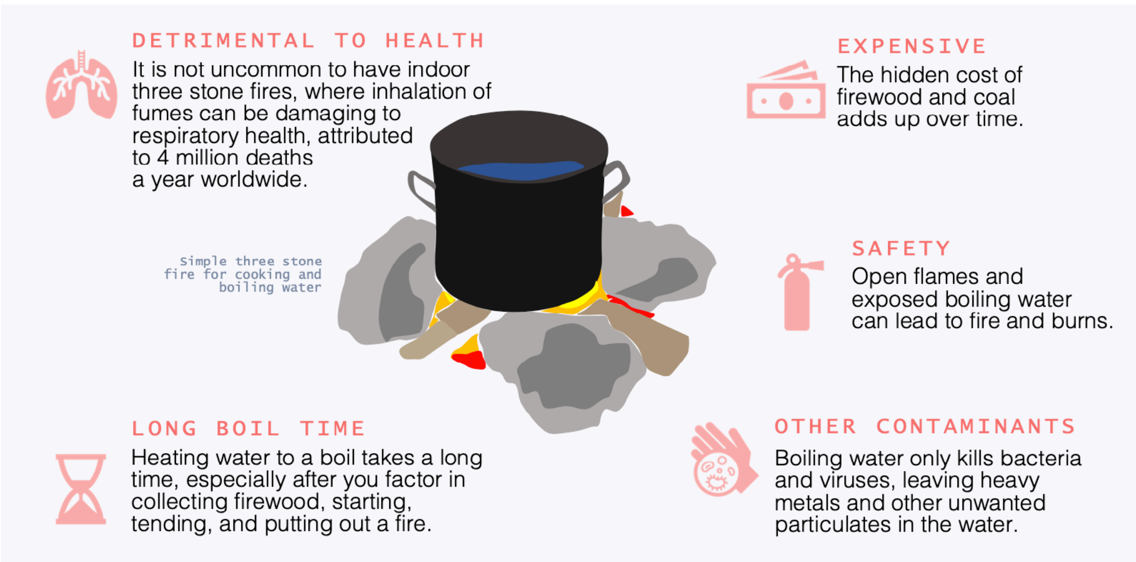


Figure 2: Infographic showing the problems of boiling water over a three stone fire.

The infographic, Figure 2, shows the problems of the most common method currently used to boil water.

1.1.3 Solution Outline

The infographic in Figure 3 shows a schematic for this project’s intended solution. This initial schematic shows features that were identified in the TFS portion of the project.

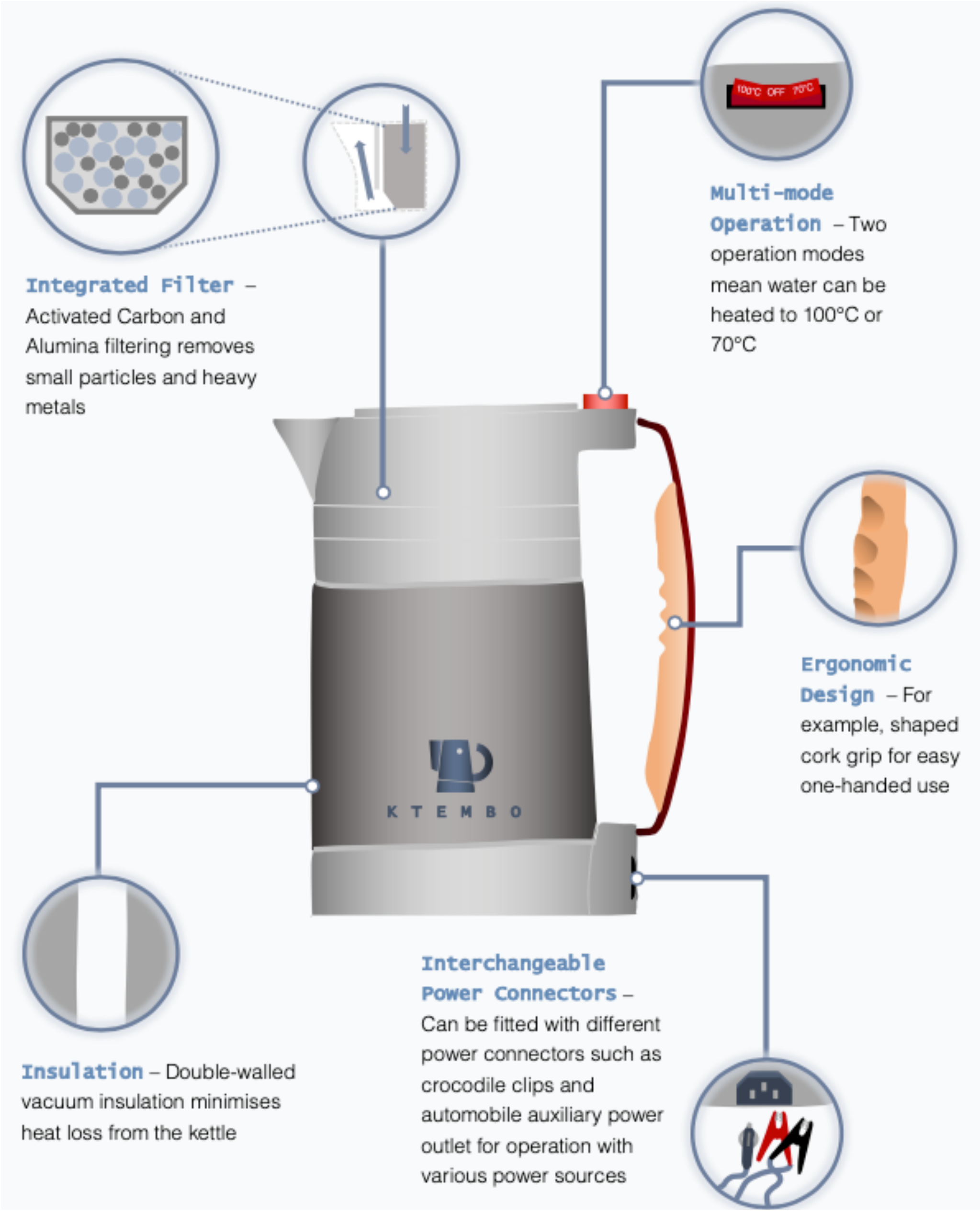


Figure 3: Infographic of the initial proposal and intended design.

This solution provides a method of boiling water to Kenya, a DC vacuum insulated kettle with an integrated filter. The insulation minimises heat loss meaning the water will retain its heat for many hours and the kettle will not have to be re-boiled. This saves the user both time, and cost associated with energy use. The activated carbon and alumina filter removes contaminants that cannot be removed via boiling.

1.1.4 Overview

The following table shows the format of this report and how it has been split up into 6 sections.

Table 1: Shows each work package for this final design report

Section	Team Member	Description
Introduction, Integration and Management	P. Lavender-Jones	Provides context of project, how it was integrated and managed
Filtering	N. Wan	Design report on filtering subsystem
Top Casing	L. Evason	Design report on top casing; including spout, latch and hinge
Casing, Base and Power Cable	L. Peacock	Design report on insulation, base and power cable subassembly
Heating and PCB	C. Everist	Design report on heater and PCB electronic design
Project Proposal and Conclusion	P. Lavender-Jones	Final proposal of solution and conclusion of project

This is the final report for the GBDP and follows on from the work done for the VoC presentation, TFS and business report, alongside the work for the EfA design challenge for EWB.

1.2 Design

1.2.1 Design Process Summary

This project has been following a user-driven development framework. This is to make sure that we follow the challenge brief of providing valuable impact to people's lives.

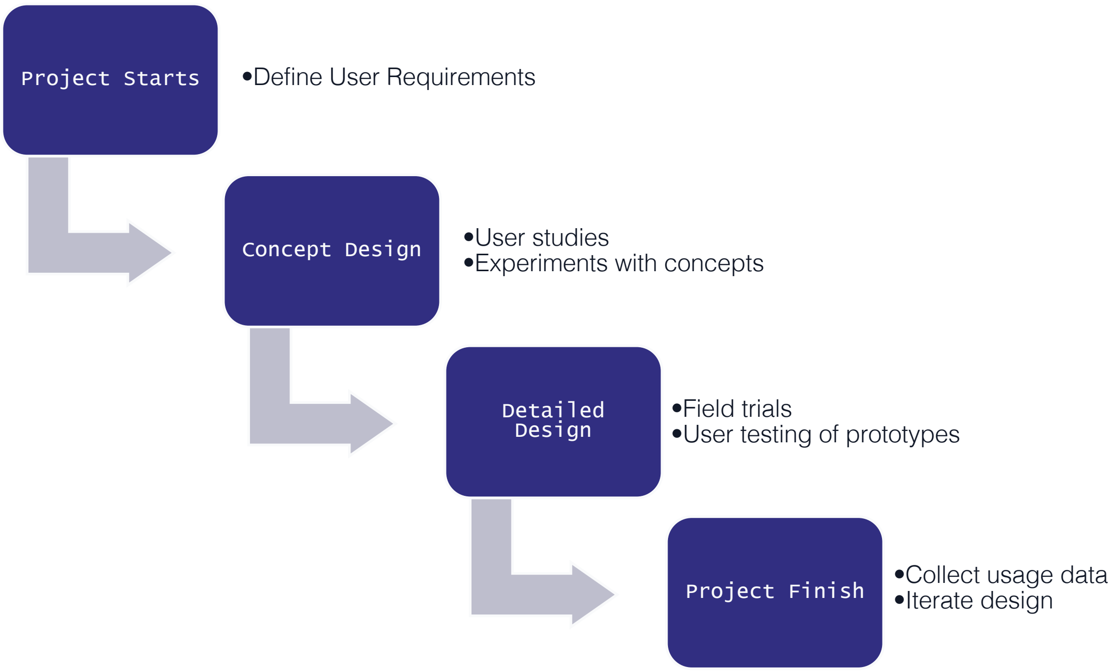


Figure 4: User centred or user driven development framework

The process in Figure 4 shows the project from start to finish. For example, in the concept design stage, sketches were used to generate ideas and can be seen in Figure 5.

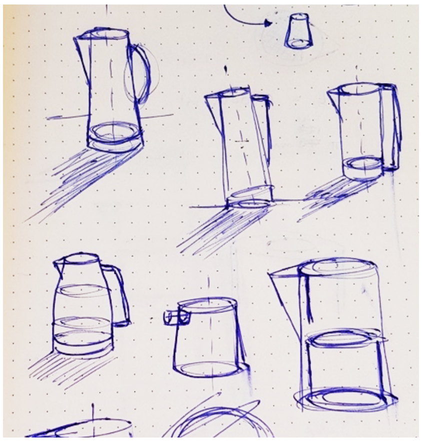


Figure 5: Concept sketches of body and spout design

Another example of concept design was a user study that was conducted to investigate the potential benefits of the proposed reduced boil time. Volunteers were asked to follow the subsequent set of rules to simulate the user experience of boiling water in rural Kenya:

1. For the first two weeks, experiment subjects were requested to set a one-hour timer before boiling or drinking water for any purpose. They were then requested to make comments regarding any inconvenience they may have faced.
2. For the third week users could reduce this timer to 10 minutes and note any improvements to the previous inconveniences of the one-hour boil time.

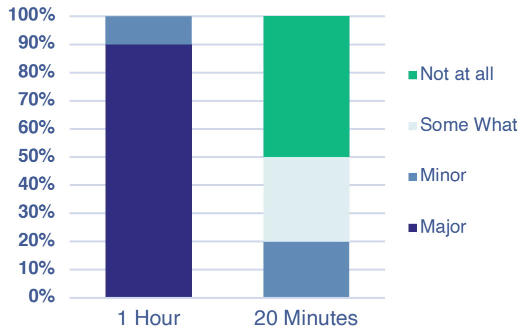


Figure 6: Response to the effect that a one-hour boil time had to daily life compared to 10 minutes.

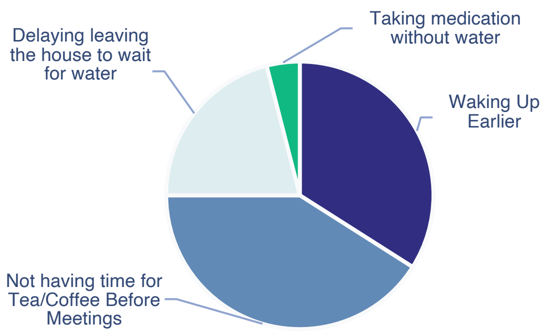


Figure 7: Sources of inconvenience when having to wait one hour for water.

It is worth noting that this does not capture the issues faced by those in Sub-Saharan Africa who have to tend to the fires and cannot leave them unattended as this experiment allowed us to do. Simulating the user experience affirmed shorter boil times would greatly benefit our end user.

1.2.2 House of Quality

The HoQ done at the beginning of the project was revisited to see if the customer aims that were initially identified had changed. Although the weights had changed slightly it is clear that build quality, serviceability and safety are still the most important quality characteristics. The full analysis can be seen Appendix A.

1.2.3 User Profile

Building on the user profile done for the VoC stage of the project, more research was done to get a representative for a typical day and use case of a kettle; this is shown in the infographic below.

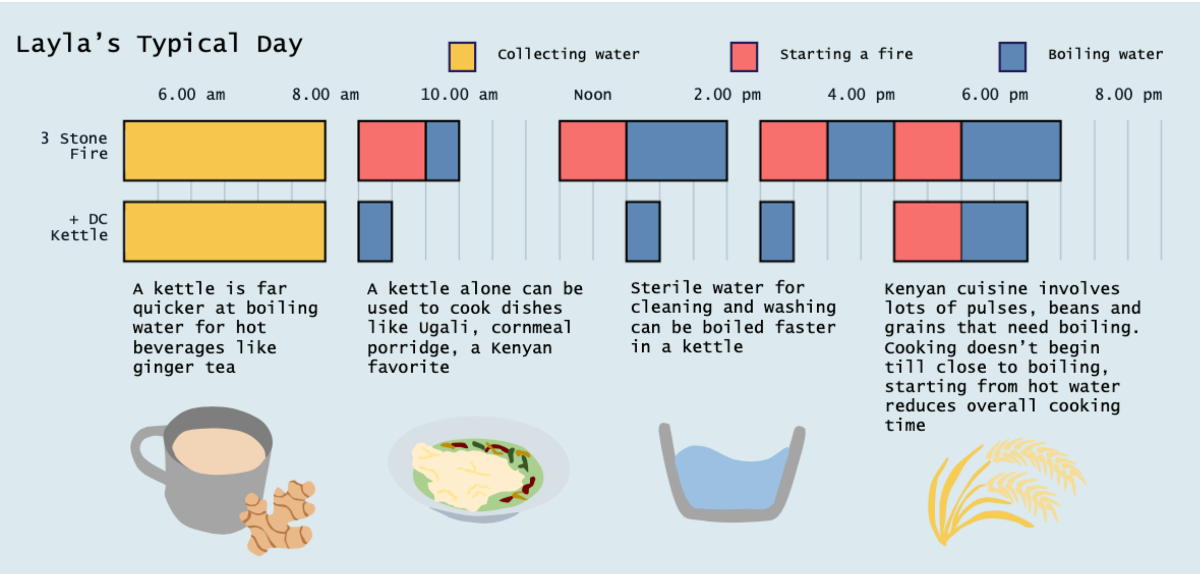


Figure 8: Infographic showing the potential time saving of a kettle

The user is most likely female and like most Kenyan women, they could spend at least 4 hours a day on unpaid domestic work, on top of weekly tasks such as collecting firewood. A kettle cannot eliminate all of this, like collecting water each day, but it can reduce domestic burden.

1.2.4 Product Design Specification

The PDS was updated with new requirements from the TFS, updated HoQ, user study and user profile. A snapshot of this is shown in Table 2.

Table 2: Snapshot of the PDS for this project

Category	Requirement	Target	Must/Wish	Method of Evaluation
Performance	Fast cycle time	30 mins/litre	Wish	Simulink model and hand calculations
	Fast boil time	20 mins/litre	Wish	Simulink model
	Filter time	10 mins/litre	Wish	Hand calculations and experiments
	Weight	< 2 kg	Wish	CAD designs
	Energy efficient	>60%	Must	Simulink model and hand calculations
	Heat water to safe temperature	65°C for 1 min or 100°C	Must	Simulink model and hand calculations

Reliability	Remove harmful contaminants	To safe drinking level	Must	Filtration feasibility study and design validation experiments
	Stable	Must not fall over easily	Must	Check CAD for centre of mass
Conformance	Locally manufactured	In Kenya	Wish	Manufacturing feasibility study
	Safe	Adhere to KS277:1980	Must	Electronic circuit design
	Affordable	<£30 BoM cost	Must	Bill of materials calculations
Durability	Product must have a long lifetime	15,000 cycles	Must	Selecting durable materials and manufacturing processes
Serviceability	Easy to repair	90% of parts replaceable	Must	CAD to ensure permanent joining methods are minimal
Features	Easy to use	One handed operation	Must	CAD and operation sequence
	Large boiling chamber capacity	1.5L	Wish	CAD and Simulink
	Large filter chamber capacity	1.5L	Wish	CAD and Simulink
	Multiple power connectors	Connections to all common sources	Wish	CAD design

1.2.5 Current Market Alternatives

The DC kettles that are currently available are basic and were found to typically have the following specifications [6]:

Table 3: Product specification for a typical DC kettle

Materials	Stainless Steel AISI 304 ABS
Max Capacity	1L
Voltage	24V/12V
Efficiency	~50%-68%
Power	250W/150W
Boil Time	25 mins / 50 mins
Dimensions	180mm, 160mm, 143mm
Cost	~£16

Current DC kettles are not designed with efficiency or durability in mind, there is opportunity for better design.

1.2.6 Design Decisions

Early in the design process, governed by both the PDS and the team's capabilities there were key design decisions that were considered and upheld throughout the project.

To keep manufacturing costs at volume low, injection moulded plastic was heavily utilised. This is because although tooling costs can be high, the marginal cost of producing a part is minimal as small parts can be combined into a single mould. Injection moulded plastic also has the advantage of making it easy to design snap fits. Snap fits are a common joining method of plastic parts for their simplicity, cost and, if well-designed, robustness. With no moving parts and low part count, they should minimise manufacturing and repairing costs. This also means that individual parts can be easily replaced.

Reducing part count decreases bill of materials cost and improves serviceability. To aid this, an early decision was made to remove the detachable base that most AC kettles would have. This simplifies the electric design, suiting our group's skills.

Similarly, although the design could have been achieved using passive electrical design, a PCB was used as it allows for boiling modes to be achieved via a microcontroller instead of a complex passive circuit design which our group did not have the resource to design.

There is no external fill window as this increases manufacturing complexity to create a thermally insulated boiling chamber. This is a trade-off for cost and usability, where cost has outweighed the benefit of seeing how full the kettle is without opening the lid.

1.2.7 Material Selection

Any surface that comes in contact with the water in the kettle must be food safe, as per the requirement in the PDS. This meant that materials were carefully selected to ensure that they would not contaminate the water.

Stainless steel comes in many grades, the most common being AISI 304. This is a food safe alloy and is also medical grade. 304 is cheaper than the similar alloy, 316, which has better corrosion resistance [7]. Since the stainless steel will only be in contact with clean water, corrosion is less of a problem. And 304 has been chosen as the preferred stainless-steel alloy.

Similarly, when choosing a polymer for injection moulding, the food safe and medical grade material of polypropylene was chosen. It is widely used in medical and food applications for its heat resistance and high chemical resistance. Some properties of the material are shown in Table 4.

Table 4: Temperature related material properties of polypropylene

Temperature	Value
Melting	165°C
Softening	152°C
Maximum Operating	143°C

Since the kettle is at atmospheric pressure the latent steam will be at a 100°C. Thus, the maximum operating temperature is lower than the maximum temperature with 40°C of headroom.

1.2.8 Sustainability

One way of reducing environmental footprint is by making the kettle more efficient. The insulation will not only improve boiling efficiency but also reduce the need for re-boiling of water. Furthermore, the second heating mode which heats only to 70°C will also reduce the energy used, when the kettle is only to be used for cleaning water. The impact of this was studied in the Business Report, where analysis showed 1L of water boiled using traditional methods releases 0.12 kg of carbon each time.

Materials selection manufacturing methods and geometry also play a vital role in ending with a sustainable design. All materials used in our kettle are recyclable with 85% of stainless steels being recycled at end of life and the average recycled content being 44% [8].

1.2.9 Regulations and Standards

The kettle's target market is Kenya, and so must follow the Kenyan Standards. There have been recent pushes to specify Minimum Energy Performance standards as a method of improving energy efficient appliances in Kenya. Our kettle must adhere to KS277:1980, the Specification of Electric Kettles for Household and Similar Use [9]. Since, this standard is not publicly available, the suggested related Indian Standard IS-302/IS-367 was used where appropriate.

There is no standard DC power connector for solar appliances in Kenya. However, there are common connectors for other uses. A 2P Compact Power Connector was chosen as it is widely available allowing us to design a schematic for a power connector that we can open source and make freely available for third parties to manufacture. This also means that we can provide just one connector with crocodile clips which are versatile catering for as many people as possible without creating unnecessary e-waste by providing other potentially unused connectors. It also allows for people to use the kettle with car batteries, a common power storage method in Kenya.

1.2.10 Iteration

The design was constantly iterated upon via design reviews within the team, until a final design was decided upon. Each review would critically link the design changes to the PDS but more importantly the intended user. This can be seen in Figure 9 and Figure 10.

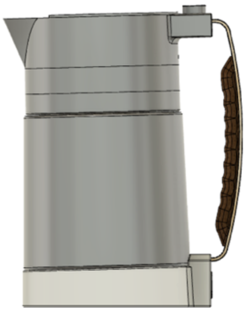


Figure 9: Initial design iteration

Figure 10: Final design iteration

1.3 Systems Integration

Analysis was carried out to determine the extent to which sub-systems rely on each other and the overlap between them while designing. Planning the system integration also allowed for the project to stick to the development timeline and brought better visibility on which features depended on other features, so they could be completed first.

For Technical Drawings please refer to the drawing pack.

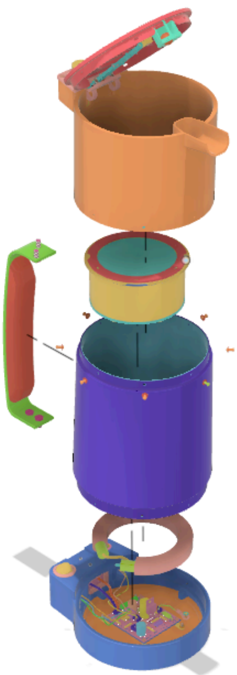


Figure 11: Exploded view showing different components of the design

1.3.1 Sub-System Breakdown

The kettle is made up of 7 top level subassemblies: the top casing, filter, casing, heating element, base, handle and power cable. The relationships between these subsystems are shown in Table

5 where ▲ (3) is a strong, ■ (2) is a medium, and ● (1) is a weak relationship; the total scores are shown in the highlighted cells.

Table 5: Relationship matrix of subsystems

	Top Casing	Filter	Casing	Heating Element	Base	Handle	Power Cable
Top Casing	8	▲	▲			■	
Filter		4	●				
Casing			10	▲	▲		
Heating Element				7	▲		●
Base					11	■	▲
Handle						5	●
Power Cable							5

From the matrix, it is clear that the casing and base have the most relationships with other systems. However, this information alone is not particularly useful. In addition to top level subassemblies, there are also lower-level subassemblies, these are shown in Figure 12.

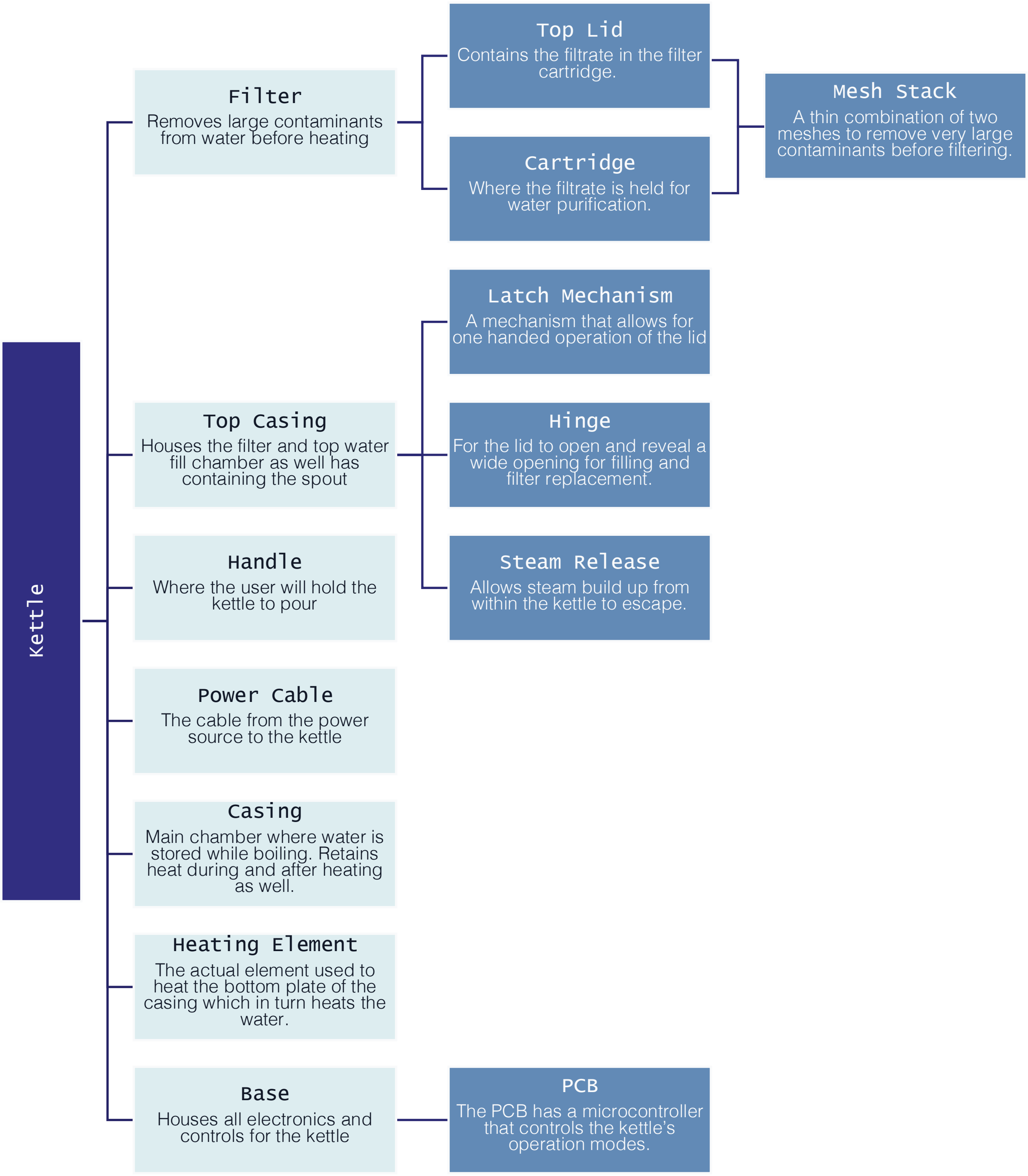


Figure 12: Subsystem tree diagram.

Both the relationship matrix and the subassembly diagram were used to map the major parameters between each subsystem. This determined how each sub-system interfaced with the other systems. Figure 13 shows a dependency diagram, where the arrows display important parameters that drive the design of each system. The arrows show if the relationship is one-way or bidirectional.

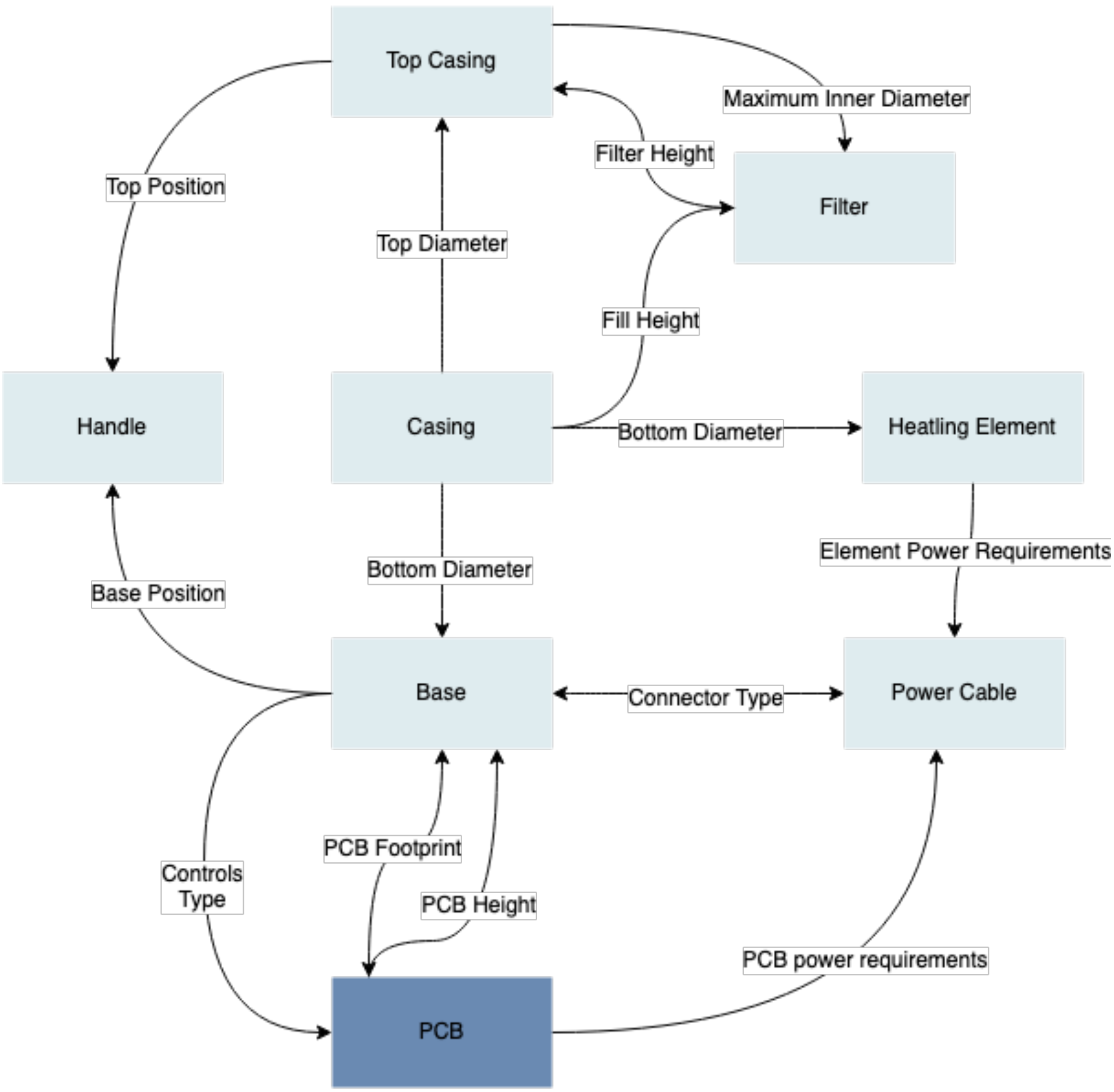


Figure 13: Dependency diagram showing relations and important parameters.

The diagram includes the PCB, because although it is not a top-level subassembly, it drives the parameters of a few other top-level subassemblies. From Table 5, the sub-systems with the highest relationship score were the casing and base; this is reflected in the dependency diagram. The diagram shows that while the base has slightly more relationships that the casing, it is driven by more parameters than it dictates. Sub-systems which dictate more parameters, like the casing, were designed first. Parameters from within a sub-system were determined by the PDS. For example, the top and bottom diameter of the casing was determined by the desired volume of the kettle.

1.3.2 Physical Prototyping and Experiments

Access to labs, workspace, tools and physical prototyping resources has been limited this year, however the best efforts have been made to experiment as much as possible. Cardboard prototypes were constructed for general sizing of the kettle and to test the ergonomics of having different sized bodies. The initial CAD design was found to be far too large when prototyped from cardboard.

Figure 14: Carboard prototyping of full assembly.

Using the project budget that is assigned to each group, an existing insulated kettle was bought for experimenting. It was initially used for tests on thermal efficiency and cooling rates to try and get a better understanding of practical thermal transfer rates. However, another unintended use for the kettle was to reverse engineer parts to see how the manufacture tackled problems like sealing the lid or heater arrangement.

Figure 15: Kettle bought to experiment and test with.

1.3.3 Thermal Modelling

A revised thermal model was constructed to better represent the design. The original model assumed insulation was a foam wall; after the TFS the insulation was known to be a double walled vacuum. Thus, the model was updated to reflect this design decision and updated using more accurate thermal coefficients using the specific stainless-steel grade, 304. Similarly, the power function was fixed to represent the final circuit, a maximum power of 300W.

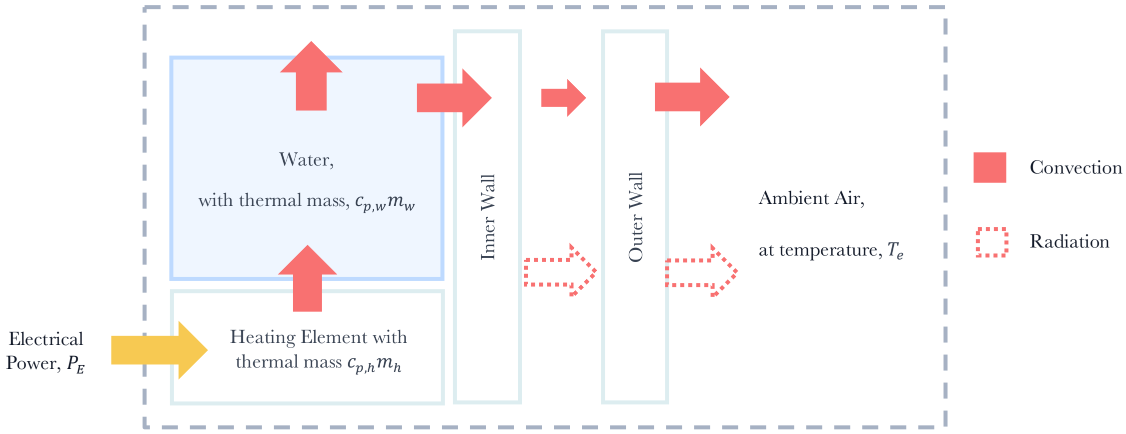


Figure 16: Updated thermal model of Simulink kettle.

As with the TFS, limitations from modelling the system as a lumped capacitance are still present. Since the heat transfer coefficients, emissivity and specific heat capacities have been tuned, the error from inaccurate values has been reduced. However, since the largest errors come from this model not incorporating geometries, data gained from this Simulink model has to be used with caution.

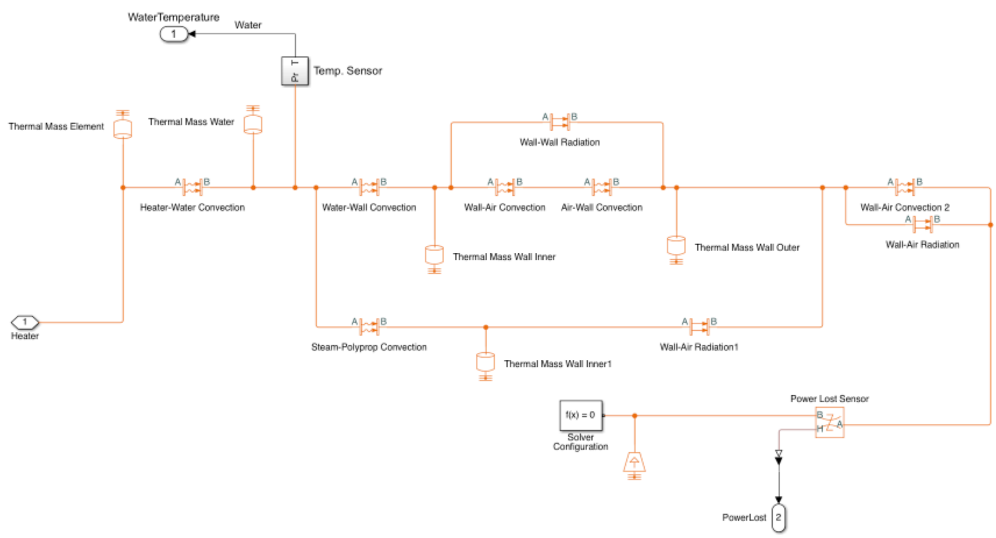


Figure 17: Simulink thermal heat model of kettle.

1.3.4 Centre of Mass

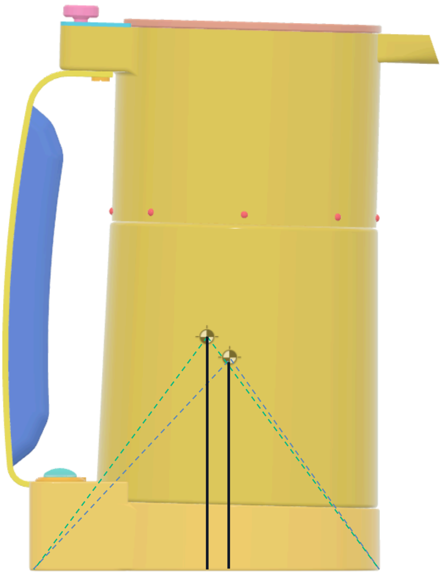


Figure 18: Centre of mass analysis in different scenarios.

The kettle has been designed on a slight 3-degree tilt, making it easier to lift off of a surface. The centre of mass is slightly closer to the handle improving usability with one hand. To ensure that the design was adhering to the PDS requirement of being stable and therefore safe, the centre of mass was calculated in two extreme scenarios; with the top chamber filled with water and empty below, with the bottom chamber filled and empty above. The centre of mass must be in a similar place in both situations to minimise risk of the user expecting the centre of mass to be different and spilling the water and burning themselves, especially as there is no external view on how full the kettle is. As shown in Figure 18, the centre of mass in both scenarios act in a similar central location of the base making it stable and less likely to spill from toppling.

1.3.5 DFMEA

To understand the possible technical risks associated with the product, an FMEA was produced, highlighting the highest risk items by calculating the Risk Priority Number (RPN). Using this, additional measures in the design and manufacturing processes can be introduced, mitigating the potential risks. The chart below shows the potential causes of product failure, demonstrating the different RPN between the original and managed risks. Full table is shown in Appendix B.

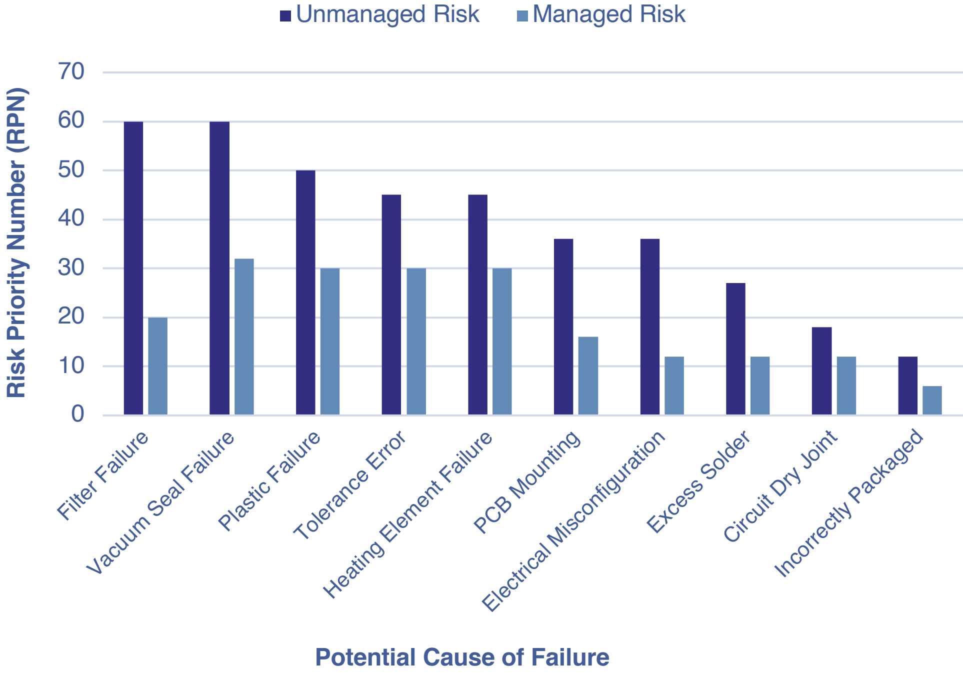


Figure 19: RPN before and after managing the risk

1.3.6 Error Tolerant Design

As well as ensuring tolerancing was designed for in individual subassemblies and part drawings, tolerancing needs to be considered for the whole system as well. Tolerance stacking means that small tolerances in unrelated areas of the design could amount to a large error in another. The likelihood of this was mitigated by having interfaces with compressible O-ring seals or rubber gaskets as shown in Figure 20.

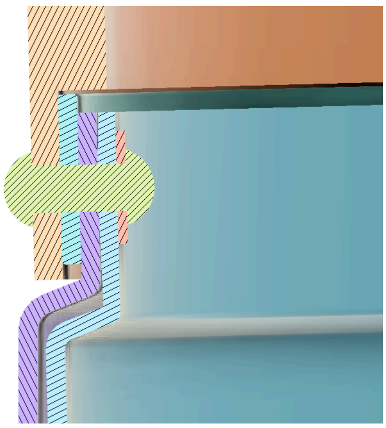


Figure 20: Joining between top casing and stainless-steel casing with rubber seals and gasket in-between.

The handle subsystem is mounted at the top and bottom on to the top casing and base respectively. To account for manufacturing and assembly differences between each kettle, the screw holes were designed with Poke-Yoke, or mistake proofing, in mind. There is a slot and hole at both mounting points meaning small differences in position are accounted for.

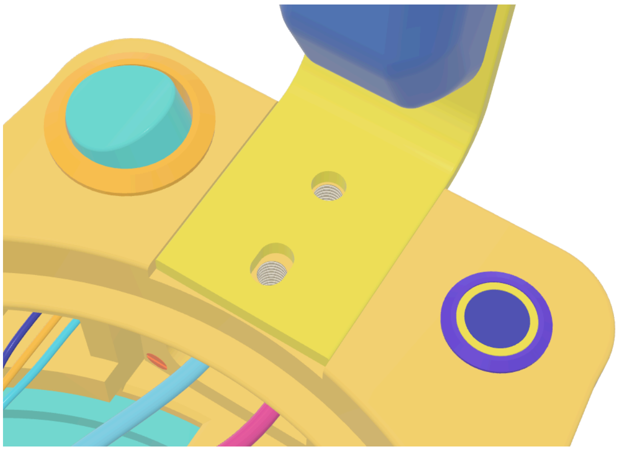


Figure 21: Slot and hole design for joining of handle to bottom base.

1.4 Project Management

The project continued using the Jump and Dive approach, still focusing on user centred design. With a small team and a more novel than routine problem, the management style was less rigid than for some other teams. The team charter helped govern the efficient and smooth running of the project while being fully remote. Daily team stand-ups, allowed work and resources to be allocated efficiently; each morning every team member would briefly discuss:

- What they have done
- What they are doing
- What they need help with
- If anything was blocking them

This was in addition to me proving reminders of any upcoming deadlines or news filtered through from the weekly PM meetings.

Communication	Values	Processes
• Daily 9AM stand-ups • Weekly meetings with supervisor • Monthly meetings with EWB mentor • Communicate problems early • Let people know if you are unable to attend a meeting	• Core hours of 9AM to 5PM • Take ownership of your own work • Be on time • Work to the best of your ability	• Make sure key decisions are documented • Back everything up • Try and be clear and concise • Factor in redundancy

Figure 22: The team charter

The group employed a flat structure for the duration of this project. Especially since there were only 5 people on the project, as well as project management, I also did design, research and technical work. Each member was in charge of their own work packages which consisted of 1 or 2 large sub-systems.

1.4.1 Work Breakdown

Initially Monday.com was used to track tasks and actions for each team member. However, it was found that this was hindering productivity as it required me to add and track everyone's tasks. The project management overhead was not being translated into productive work, so we stopped using Monday.com. Instead, the built-in task tracker in Microsoft Teams was preferred as it was tightly integrated with the calendar and messaging services which we already used.

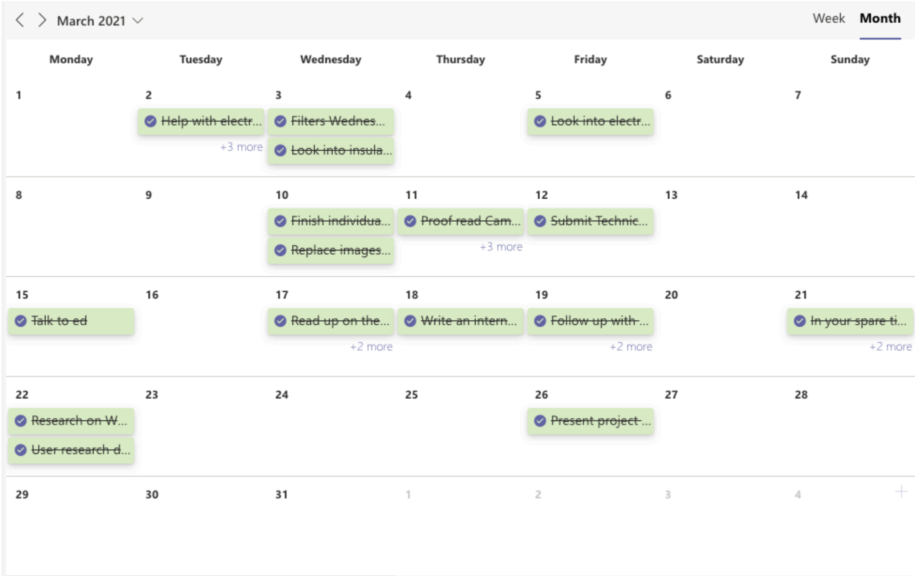


Figure 23: Screenshot from calendar plan of tasks on Microsoft Teams.

1.4.2 Milestones

Since the TFS, this project has had 3 university and 2 external EfA deliverables before this final report deadline. Each of those has been treated as a milestone. In addition, every deliverable has an internal deadline within the team 2 days before the final deadline. This gives the team slack for unexpected events or to correct errors. Every deadline was handed in at least 12 hours ahead of the deadline, if not over 24 hours before.

Table 6: Milestone and deadline calendar weekly view

April 4	11	18	25	**May** 2	9	15	23
	Executive Summary Draft			Business Report			
					Design Freeze	*Final Report*	
	EfA Final Report						
	EfA Video						

Despite the slack, some submissions took much longer than planned for. The business report took far longer than expected to format and calculate credible finances. Part of this was due to not having experience in this area and thus underestimating tasks but also because we had to learn about accounting for example while researching and writing the report.

1.4.3 Stakeholder Management

Since we are participating in the EfA design challenge, as well as internal university stakeholders, the project has external stakeholders. After handing in a concept note to EWB, we were given an industry mentor that best matched our appliance and market as a contact to get support from. We have been paired with Katherine who works for M-Kopa, a solar appliance company in Kenya. They have pioneered the pay-as-you-go business model in solar product and are at their core a connected asset financing company for customers who would not traditionally be served by financial services. Since our first meeting we have had monthly meetings with Katherine, to discuss our progress and gain an insight into the industry. She works for M-Kopa Labs, the R&D division of the company and so she was able to provide us with commercial details and important customer data that we would not otherwise have access to.

Another external stakeholder is Chandni, who owns and operates a solar business in Kenya. Although we have not had any meetings with her since the initial call at the beginning of the project, I have been in constant contact with her to update her on our progress.

1.4.4 Training

The team has required significant training and up-skilling due to being without an electrical engineer. A team member has had to teach themselves, with little external help, about electronic circuit design. Naturally, this has taken more time that it would have taken someone who already had the skills to do so from the beginning. This has meant we have been under resourced for the mechanical design with CAD. The risk of not having the resource to carry out any electrical design work has been successfully mitigated at the expense of other areas in mechanical design. However, this was necessary and overall, the work carried out shows that the group has been successful.

1.4.5 Conflict Resolution and Feedback

Regular individual one-on-one calls meant there was opportunity to get feedback on management style and practice as well as provide feedback the other way. I was able to implement requested changes like summarising meetings at the end to reiterate key decisions made.

1.4.6 Access To Software

Due to working remotely and increased demand for remote access of university computers, the team only had access to software available for our own laptops. A decision was made to use Autodesk Fusion 360 for CAD, it is slightly less intensive to run and was available for both Mac and Windows unlike Inventor. On the whole Fusion is a satisfactory software to design on, however it has a few quirks that put in places some limitations for the team. It is primarily for hobbyists who want to 3D print and so doing complex joints and mechanism design was challenging. Similarly, the drawings features are not as complete as Inventor, so the team had to work around that. 2 team members had limited prior experience with Fusion, everyone else had none. We all had to learn how to use it while working on this project. Fusion does have some benefits; it allows for easy collaboration on parts and assemblies and has an integrated renderer for visualising designs.

Fusion's built-in simulation packages were used. However, they are fairly basic and minimal, access to better software like COMSOL would have enabled better thermal design.

1.4.7 Risks

The ongoing risks register was used to triage potential risks and mitigate them. On top of risks and mitigations already mentioned in previous parts of the report, a snapshot of risks is shown below.

Table 7: Snapshot of the risk register

Issue	Severity	Probability	Priority	Mitigation	Resolved?
Lacking electronics ability in team	High	Medium	High	Get help from Nathan and design for minimal electronics	Yes
No CFD experience within team	Low	High	Medium	Use MATLAB instead to do simple heat transfer modelling	Yes
No access to Inventor CAD software	Medium	Medium	Medium	Use Fusion360 instead of Inventor for all CAD	Yes
No access to Multiphysics modelling	Low	High	Medium	Use MATLAB where possible and/or hand calculations	Partially

2 Filter

2.1 Summary

A filter has been designed, incorporating 100g of activated carbon and 50g of activated alumina per fill. These granules are both around 1mm in size, purifying 16.7L for each refill and lasts 1 week. It will take an estimated 45 seconds to filter 750ml of water through the cartridge filled with filtrate. This filtrate will cost 9p per fill so can be affordable and be packaged in paper sachets. The filter cartridge will cost £2.84 in raw materials, excluding manufacturing and labour. Two mesh discs encase the filtrate above and below. These mesh discs compose of a sheet of grade 304 stainless steel mesh of size 30 mesh, removing contaminants of sizes greater than 595 µm, and a polyester textile of size 120 mesh, removing contaminants greater than 125 µm. These are fastened together with the pressing of stainless-steel sheets. The mesh discs are reusable and can be removed to be rinsed off of dirt. They are secured by Snap-on constraints in the lid and at the cartridge bottom. The filter has been designed to remove harmful metals: iron, fluoride, cadmium, manganese and other dissolved contaminants, as well as suspended matter, turbidity, and odour. The cartridge is made of polypropylene and will not deform or release harmful chemicals under the highest operating temperature of 100°C. The cartridge top and body reaches around 30°C, sustaining user safety when handling straight after boiling water.

2.2 Introduction

Kenyan natural water has been found to be typically excessive in iron, fluoride and turbidity [10]. A filter will be able to remove physical contaminants such as insects and gravel, and dissolved chemical contaminants such as iron and fluoride, in order to improve the quality of drinking water. Dirty water is the main cause of diarrhoea which accounts for 15% of deaths in Kenya [11].

Filtration requirements may be different across different geographical locations and thus the design of this filter will be specific for our Kenyan market, with possible filtration adaptations to suit the treatment of different typical water qualities in different regions.

Filtration is the first sub-system the water will pass through when entering the kettle. It will be responsible for removing solid matter and dissolved harmful metals whilst it also should reduce turbidity. The filter will sit inside the kettle directly below the lid. After filtration, the water will relocate to the boiling region by gravity.

2.3 Market Analysis

Kettles with incorporated filters exist for AC power supply in the western market. Examples include BRITA – Russell Hobbs kettle, and BRITA – Breville water dispenser.

Breville hot water dispenser with filter, £80   Russell Hobbs kettle with filter, £24

Figure 24 – AC powered Kettles with filters.

DC electric kettles in Kenya are unavailable with filters integrated within the appliance. This is likely because the water quality is drastically worse compared to the UK, hence requiring more specifications in contaminant removal and larger sized filters. Consequently, kettle appliance companies may have deemed it unsuitable to embed effective water purifying filters into a kettle, which will fit in size and pre-treat the water effectively before boiling. There is therefore an opportunity to design and market a filter embedded insulated kettle for rural Kenya.

Figure 25 – Domestic water Filters in Kenya.

2.4 Design Specification

The Kenya Standard for Potable water defines acceptable limits of contaminants in natural and treated water. This standard is used as a guide for which chemical treatments could be used and to quantify the amounts required when looking at existing natural water qualities across Kenya.

Ignoring microbiological contaminants that should be killed in the boiling process, inorganic contaminants found in three water quality assessments covering 48 sampling points are summarised below in Table 8 [12] [13] [14].

Table 8 – Contaminants exceeding acceptable limits as defined by the Kenya Standard for potable water [15].

Contaminants	Amounts found in natural Kenyan waters	Acceptable Limits	What can reduce this
Turbidity	12 to 26.7 ± 6.0	5 NTU	Activated Carbon, layers of fabric, Zeolite
Iron	0.001 to 1.5 mg/L	0.3 mg/L	Activated Carbon, Zeolite
Fluoride	0.30 to 16.6 mg/L	1.5 mg/L	Activated Alumina, Zeolite
Magnesium	75.65 to 113.38 ± 17.97 mg/L	100 mg/L	Zeolite
Cadmium	0.003 to 0.03 mg/L	0.003 mg/L	Activated Carbon, Activated Alumina, Zeolite
Manganese	0.06 to 8 ±0.04 mg/L	0.5 mg/L	Activated Carbon, Zeolite
Suspended matter	6625.67 to 12421.67 ±27.02 mg/L	NIL	Cloth (Fine meshes)

Table 9 - PDS for the filtration subsystem. ISO Standards are procedures for measuring chemical substance concentrations in drinking water.

Category	Requirement	Target	Must/ Wish	Method of Evaluation
Feature	Low cost	Filter technology costs less than £3.50	Must	CAD Design, estimated cost of materials (and manufacture)
	Design for sustainability	Reduce volume of waste materials	Wish	CAD Design, durability assessment of materials and form
Performance	Remove heavy metals	Reduce Iron, Cadmium, Manganese to safe levels as defined in the Kenyan Standard for Potable Water.	Must	Refer to ISO methods of testing mentioned in Kenyan Standard of Potable Water for each inorganic contaminant
	Remove suspended matter	Undetectable suspended matter	Must	ISO 11923 to compare with Kenyan Standards
	Heat resistant	Withstand the 100◦C boiling temperature	Must	Material selection and chemical composition must not alter with a temperature change from 20 to 100◦C.
	Reduce turbidity	<5 NTU	Must	ISO 7027 to compare with Kenyan Standards
	Allow beneficial minerals to pass	Calcium and Magnesium should be allowed to pass	Wish	ISO 7980 to compare with Kenyan Standards
	Water filtration maximal	Water must pass through all layers of the filter	Must	CAD Design, openings should be sealed off
	Not burn users	Be less than 65◦C on the surfaces likely to be touched [16]	Must	Thermal model of CAD Design
	Quick filtration time	Filtration time should take less than 60s for 250ml of water	Wish	Experimental prototyping and comparison to other products

To design a competitive filter, the PDS highlights a low costing filter targeting less than £3.50. This is because BRITA filters cost £3.50 per piece [17]. These filters take 70 seconds for 250ml to pass, as obtained from experimental studies in the TFS [10]. This is perceived as an undesirable waiting time, therefore aiming for 60 seconds or less would be an attractive feature for users.

2.5 Concept Design

Along with chemical filtration, it was suggested that using a metal mesh as the first filtrate will protect the filtration material whilst removing the larger solid matter and using a fabric cloth will improve turbidity reduction.

The options in design include:

1. Selling replaceable cartridges

  a. Using pre-existing filter cartridges
  b. Designing a unique cartridge. This would either be manufactured by an external company and sold with the kettle, or manufactured within our company. We cannot use filters marketed for water in western countries as water in less developed regions are largely untreated; the water treatment requirements are too different.

2. Selling a reusable cartridge
  a. With fabric pouches filled with filter contents. The casing would include a washable stainless-steel mesh. This would be durable but could be difficult to clean as clean water is poorly accessible for our targeted customers. It could also require pressurised backwashing which would be out of scope for a domestic kettle.
  b. With a sachet of activated carbon and alumina filtrate. The fabric layer of the filter could be fixed onto the casing or be supplied in small sheets with the sachets. A metal mesh will be a reusable element of the filter.
  c. The user can use their own filtrate with the casing instead of bags of activated carbon and alumina. A permanent fabric and metal mesh could be provided to ensure suspended matter and turbidity in the water would be reduced.

Of these solutions, a reusable cartridge will eradicate the quantity of cartridges that require manufacturing. This will save material and time resources. Providing a reusable fabric mesh with the stainless-steel mesh would also be a preference than requiring the fabric and metal mesh to be replaced. The only component of the filter that must be frequently replaced is the activated carbon and alumina which will become deactivated with usage. This can be packaged with pressed paper which can safely decompose in the environment, a likely main disposal method in rural Kenya.

2.5.1 Chemical Design

To begin with, it is understood from exploring an existing filter marketed in the UK, Brita MAXTRA, that 125g (50mm deep) of activated carbon used with ion exchange resin is used, lasting 100L/ 4 weeks [18]. This removes unpleasant odours, iron and lead. According to aquarium recommendations, 50g of activated carbon should be used for 100L of water [19]. This is suggestive that for water passively passing through without constant exposure to water, 50g of activated carbon could be sufficient for 100L of drinking water filtration. However, it is acknowledged that the different filter requirements are required for different water qualities and so is not an adaptable concept for water filtration in Kenya.

To find out the desired amount of activated carbon and activated alumina is required, it would be desirable to test actual water from Kenyan natural sources.

From the TFS, using activated carbon with activated alumina deemed most suitable to treat Kenyan natural water, which was commonly excessive in iron, fluoride, turbidity and other minerals [10]. Although zeolite removes the most chemical contaminants, it is advised against usage for organ transplant patients, pregnant women and those taking medication. This is because zeolite may distort the effects of medication. Using zeolite could therefore implement dangers to users and has not been included in the chemical design.

2.5.2 Removal of Fluoride

Activated Alumina is recognised for adsorption abilities of fluoride, as well as selenium and arsenic. The water pH should be less than 8.5 to avoid aluminium leakages [20]. Natural water in Kenya was found to always have a pH less than 8.5, so activated alumina will be safe to use [12] [13] [14].

2.5.3 How much Activated Alumina?

The Kenyan standard states that water should contain no more than 1.5mg/l of fluoride (Table 8). Activated alumina's removes 5000 mg fluoride/kg activated alumina [21]. A sample of fluoride concentration was 16.6 mg/L recorded from Langata ground water [14]. This is 1660 mg in 100L. 1660/5000 = 0.332 kg of activated alumina required to filter 100L of water.

Since excess fluoride in natural water was found in only some ground water, 330g of activated alumina could be unnecessary. Like many samples of natural water, Rungiri Quarry averaged a fluoride concentration of 0.45mg/L which was within safe limits. Therefore, reducing the amount (to 50g) could be acceptable but will require the filter to be replaced more frequently to compensate for locations with exceeding levels.

2.5.4 Removal of Iron and Turbidity

Activated carbon effectively adsorbs chemicals such as iron, cadmium, manganese, lead and arsenic. It also reduces turbidity. From taking apart a BRITA filter cartridge, it was found that 125g (50mm deep) of activated carbon and ion exchange balls were housed. This filter lasts for up to 4 weeks (100L) and so we could associate either the depth or the mass of activated carbon and alumina with the filters lifetime before requiring replacement [18]. Around half the filtrate is activated carbon so it could be assumed that about 65g of activated carbon was used.

2.5.5 How much Activated Carbon?

The acceptable limit of iron for drinking water is 0.3 mg/L. Across all three papers of Kenya's water quality, iron levels were always exceeding recommended limits. Along the Nyando river, concentrations were between 0.18 – 0.68 mg/L. Activated carbon removes iron at 0.62 mg/L (620 mg/kg) [22]. Taking the maximum level of iron found in this river, in order to remove the excess 380 mg of iron in 100L of water, we would need 380/620 = 0.613 kg of activated carbon. For aquariums it is advised to use 50g per 100L of water [19]. However, it is likely this is used with pre-treated water to urban homes.

Approximately 600g carbon and 300g alumina were calculated to be used for 100L. The filtrate provided in our design will thus have an activated carbon:alumina ratio of 2:1, 100g of each activated carbon and 50 g of activated alumina (total 150g). This is a scale of 1/6 smaller than required to fit the cartridge volume, so the filter must be changed every week (4 weeks divided by 6) for purifying 16.7L of water.

2.5.6 Prototyping

To understand what metal mesh sizes and which materials of fabric cloths are suitable in improving water quality without the expense of filtration time, 250ml of water, equivalent to the volume of a mug, was poured through these materials of 100mm diameter and timed. Materials that were tested are described in Table 10.

Table 10 – Materials tested for filtration time.

Material	Size	Filtration Time
Stainless-steel	500 mesh	Did not pass any water through
Stainless-steel	120 mesh	Did not pass any water through
Stainless-steel	30 mesh	0 – 4 seconds (Instant)
Nylon	120 mesh	5 – 7 seconds
Polyester	120 mesh	5 – 7 seconds
Activated Carbon	50mm thick	0 – 4 seconds (Instant)

From the results in Table 10, stainless-steel of 120 and 500 mesh sizes were ruled out. The two fabrics, nylon and polyester, had unnoticeable differences in filtration time and hence the decision of which fabric can be determined by material properties such as temperature resistance, water resistance and durability. Activated alumina will be of similar size to activated carbon (1mm) and will not significantly affect filtration time. However, the packing of the granules can largely alter filtration time, especially because they spread out in fluids when unconstrained. The textile will dominate the filtration time as the duration for water to pass is greatest. A smaller entrance/exit into/from the filter will increase the duration of filtration time so maximal entrance size would be ideal.

Water quality could not be tested due to available water in the UK being drastically different to those in Kenya. An electronic total dissolved fluids (TDS) meter could have been used to determine the improved removal of iron and fluoride from a sample of typical Kenyan water.

The number of layers of the chosen fabric should be counted and tested to measure how many layers can remove turbidity or produce an acceptable quality of improved drinking water.

2.5.7 Which Meshes?

Nylon, polyester, and cotton has been considered as candidates for the cloth layer of the filter. This will be of size 120 mesh and will prevent the filtrate material from escaping the filter, as well as prevent suspended matter greater than 125μm. Nylon and Polyester both have a maximum recommended operating temperature of 135°C [23]. The kettle is not designed to operate at temperatures greater than 100 °C so will be safe to use in a kettle. Compared to nylon, polyester is easy to clean, mould resistant, and resists stretching and shrinking [24]. Nylon however is more elastic; hence, is more susceptible to deformation where changes in the mesh size of the fabric will affect filtration effectiveness. Cotton is biodegradable so is likely to deteriorate faster than nylon and polyester and so would require frequent replacement. Since it would be best to make the fabric component of the filter reusable, polyester will be the most durable and therefore suit best. It is also considered food and drink safe. Doubling cloth layers will improve filtration quality but slow filtration time. Improved quality is more important than filtration time as the ultimate goal is to provide clean drinking water. Consequently, using more than 1 cloth layer has been considered.

Stainless-steel of size 30 mesh will be used to remove contaminants of sizes greater than 595μm. Stainless-steel has been selected for its high durability which is required to protect the filter from sharp and large matter. As a reusable element of the filter, this can be washable and will not require replacement unless significantly damaged to an unfunctional state. Grade 304 stainless-steel has been selected as it is widely used for filtration and food grade products. It is corrosion resistant and cheaper than others, such as grade 316 [25]. It is susceptible to pitting from chlorine and salt solutions, which are not expected to be used in conjunction with the filter.

Polyester and stainless-steel are both recyclable, signifying at the end of life for the mesh layer, these meshes can be cleaned and reprocessed without any material waste.

2.5.8 Cartridge Material and Manufacturing Considerations

A cartridge will be required to contain the activated filtrate elements, clamped with the mesh element above (and possibly below). The cartridge should be heat resistant so heat cannot be wasted through conduction of the filter and be safe to handle. This is so the user can remove the filter cartridge independent of if the water has been recently boiled. It must also be safe across a range of operating temperatures, by not releasing harmful chemicals into the water as some plastics do.

Table 11 - ABS and PP material comparison.

	ABS	**PP**
Maximum service temperature (∘C)	62.9 -76.9	66.9 – 83.9
Melting point (∘C)	NA	140 - 150
Glass transition temperature (∘C)	102 - 115	-24.2 – -16.2
Cost (GBP/kg)	1.52 – 1.79	1.03 – 1.06

Thermoplastics ABS and PP are desirable for being considered food and drink safe, BPA free and having good insulative properties. Polypropylene tends to be cheaper of the two, with a higher maximum service temperature. The cartridge is unlikely to reach temperatures above its maximum service temperature due to low thermal conduction, but this can be confirmed with a thermal analysis of the component. Polypropylene is used for BRITA filter cartridges so supports our confidence in using a polypropylene casing. It will be made from injection moulding where parts of the component with detailed snap fittings can be made in unity on the component.

2.6 Concept Development

2.6.1 Sketches

Throughout the concept development, sketches aided design ideas. Features from sketches inspired each CAD iteration to its final concept.

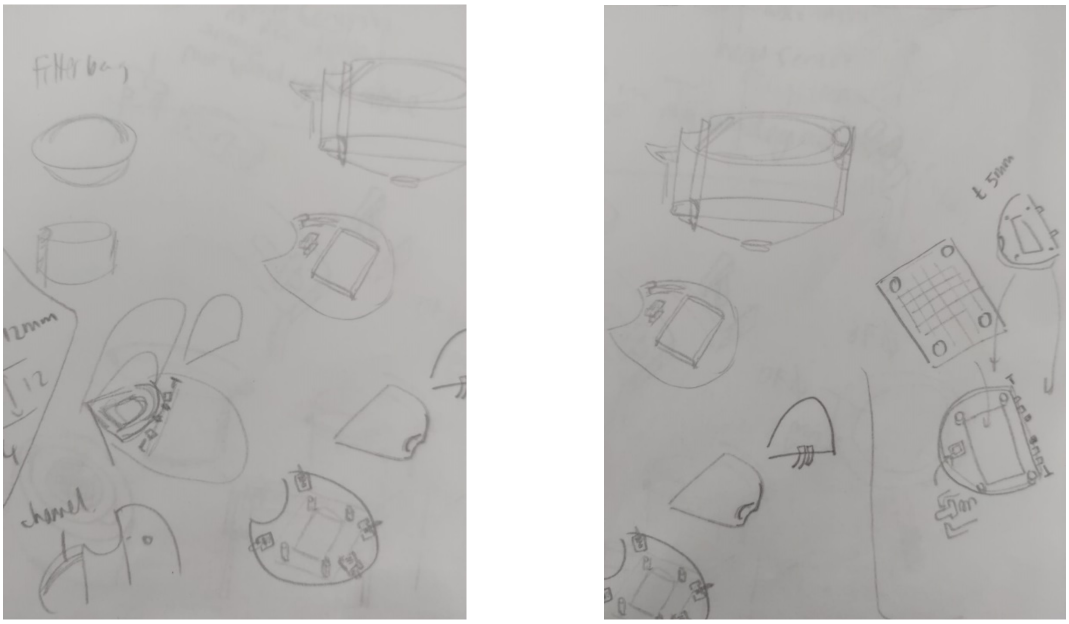


Figure 26 - Sketches of a hinged filter lid, with a built-in spring to secure closure. A semicircle design gives space to the spout.

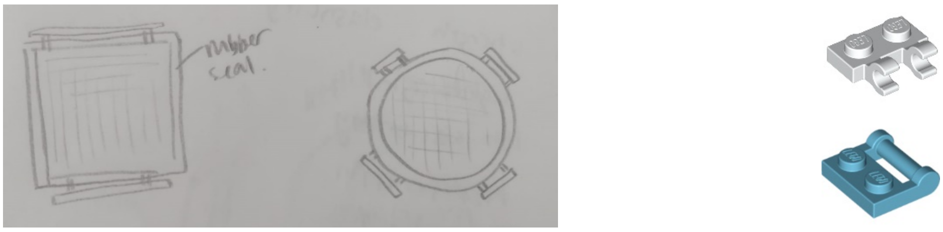


Figure 27 – Lid with mesh sketch, with locking inspired by LEGO pieces.

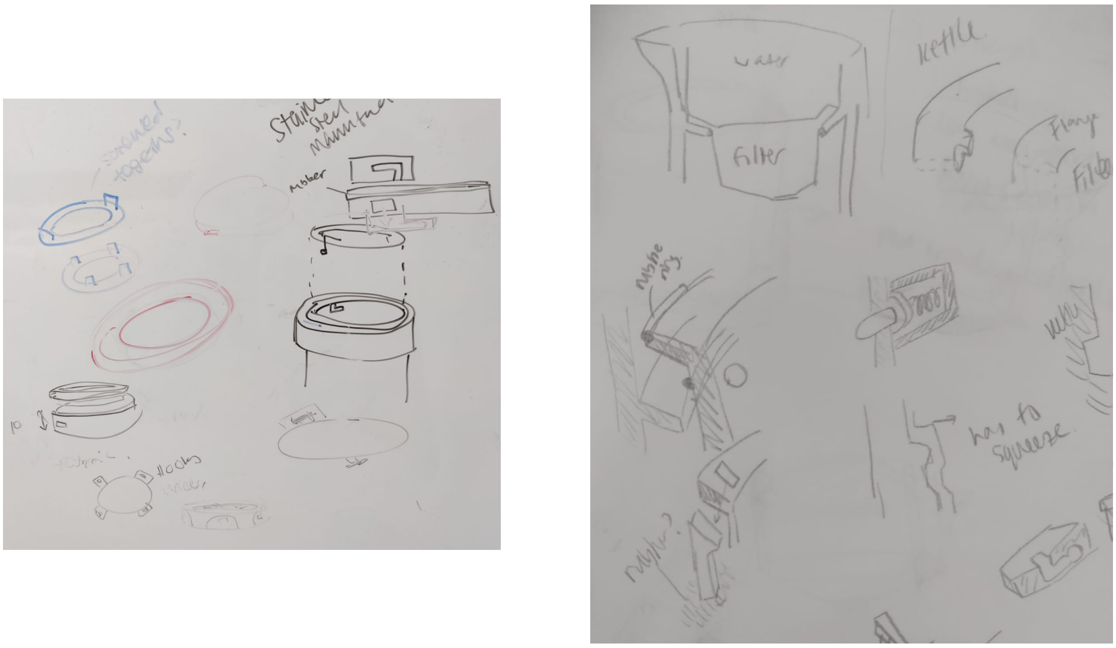


Figure 28 - Twist lock and push snap mechanisms considered for the filter lid. A spring resistive lock was eliminated as parts for this were intricate and many.

2.6.2 Prototyping

Cardboard was used to model usability engagement and assembly in designing concepts. This was to aid the initial concept starting point.

Figure 29 – Initial cardboard model of the filter cartridge with lid.

2.7 CAD Iterations

2.7.1.1 Iteration 1 – based off cardboard prototype

The initial concept has been designed cylindrical as this is the form of the kettle. The flange allows the filter to rest at the top or inside the kettle. Holes have been added to this flange where fingers can be inserted and the filter be removed. There is no mechanism to secure the lid or cartridge in place. A replaceable fabric bag carrying the filtrate is intended for this design to avoid the additional mesh fixture.

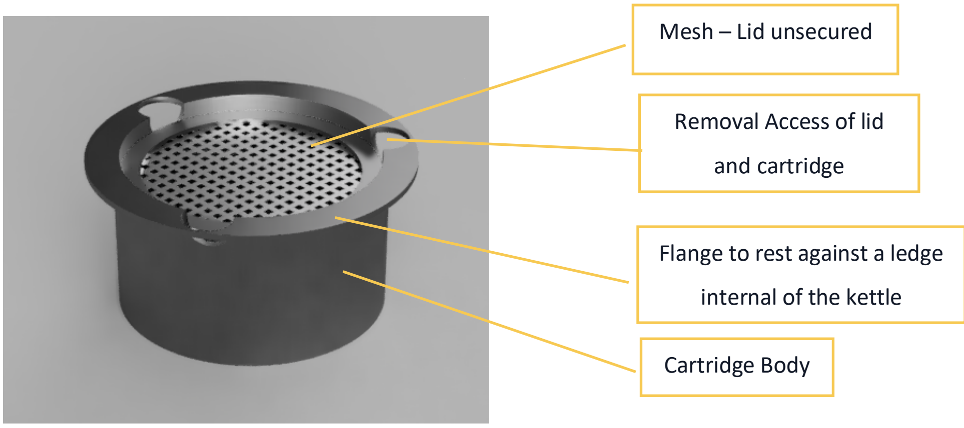


Figure 30 - CAD Iteration 1, based off basic cardboard prototype.

2.7.1.2 Iteration 2 – consideration for securing lid mechanism

To compensate for the spout and flow channel taking some space in the circular cross section within the kettle, this second iteration is no longer cylindrical to allow for vertical channels. The exit of the filter is tapered to ensure water flows downwards. Small drainage holes are added to the bottom to increase water exposure to the filtrate.

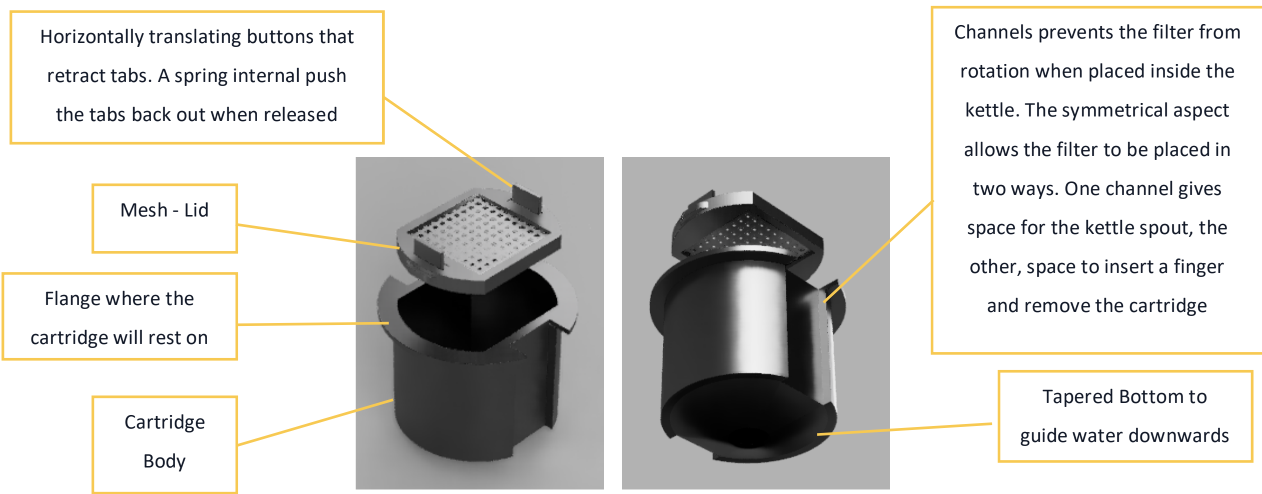


Figure 31 - CAD Iteration 2, incorporating a securing lid to keep filtrate in place.

The lid is secured on with an inward pinch mechanism that springs back to extension and grip onto the inner cartridge walls when released.

2.7.1.3 Iteration 3 – inclusion of fabric mesh fixtures

It is intended with this iteration; the cartridge will not sit aligned with the centre of the kettle. A circular form will allow the lid to have a twist lock mechanism, using locking tabs that rotate the lid to lift it off. This will mean users will not have to use strength to oppose the resistive force of springs. A rubber ring is placed above the tabs to ensure water does not go around the lid instead of through the mesh. The lid consists of the stainless-steel mesh. The top fabric is intended to be replaceable which should hook onto the tabs of the lids twist mechanism. This could be fiddly for the user. The bottom fabric should be clamped by a circlip at the bottom of the cartridge. The bottom of the cartridge also has 2mm diameter holes to allow the water to exit, positioned with conical surface around it to ensure water exits downwards. A rubber ring sits external to the cartridge so it will stay in place by friction in its holder.

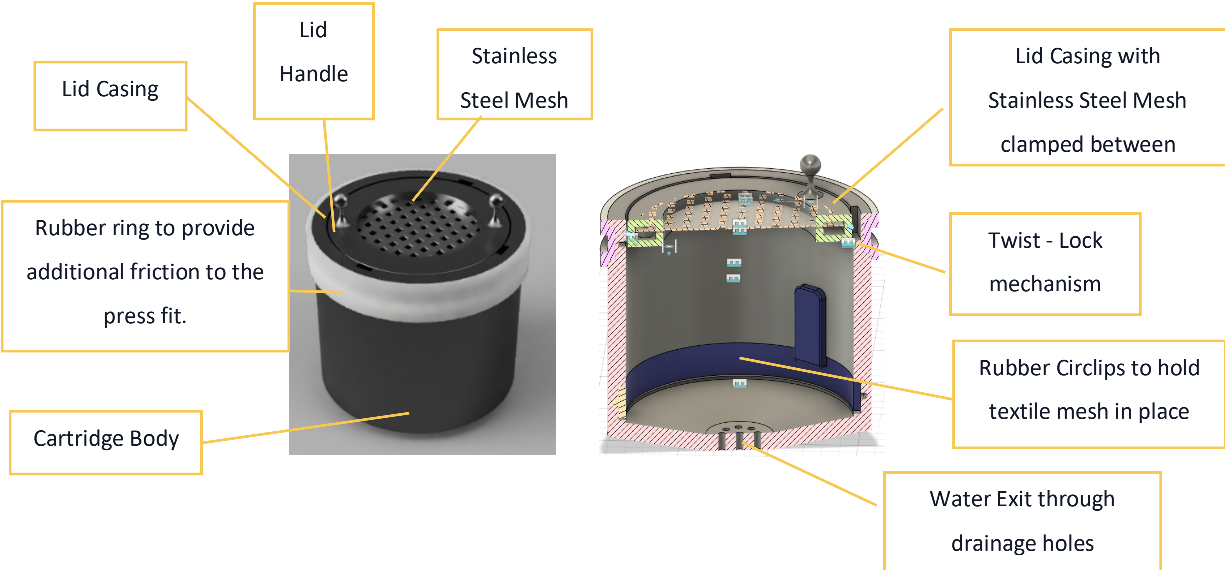


Figure 32 - CAD Iteration 3, with a twist lock lid for improved reliability in lid security.

To reduce material consumption in the design, the walls should be thinner. This will also allow greater cross-sectional area for the water to pass through, meaning greater flow rates and filtration times. There is possibility that water may not pass through the exit of 2mm diameter holes of 5mm thickness as this was not tested. Thus, the mesh at the entrance could also be used at the exit.

2.8 Final Design

The cartridge has been redesigned with a smaller wall thickness of 1mm. A mesh disc consisting of the stainless-steel and polyester textile is pressed together between stainless steel metal sheets and is used for the entrance and exit of water. Snap fittings are used to secure the mesh at the bottom and top. A small flange is used to rest the cartridge at the top of the holding, with cuts to enable users to lift the cartridge out from its press-fit position in the kettle. Reusing the top mesh disc for the bottom too mitigates the need for a tapered bottom, without having to create another mesh for the bottom.

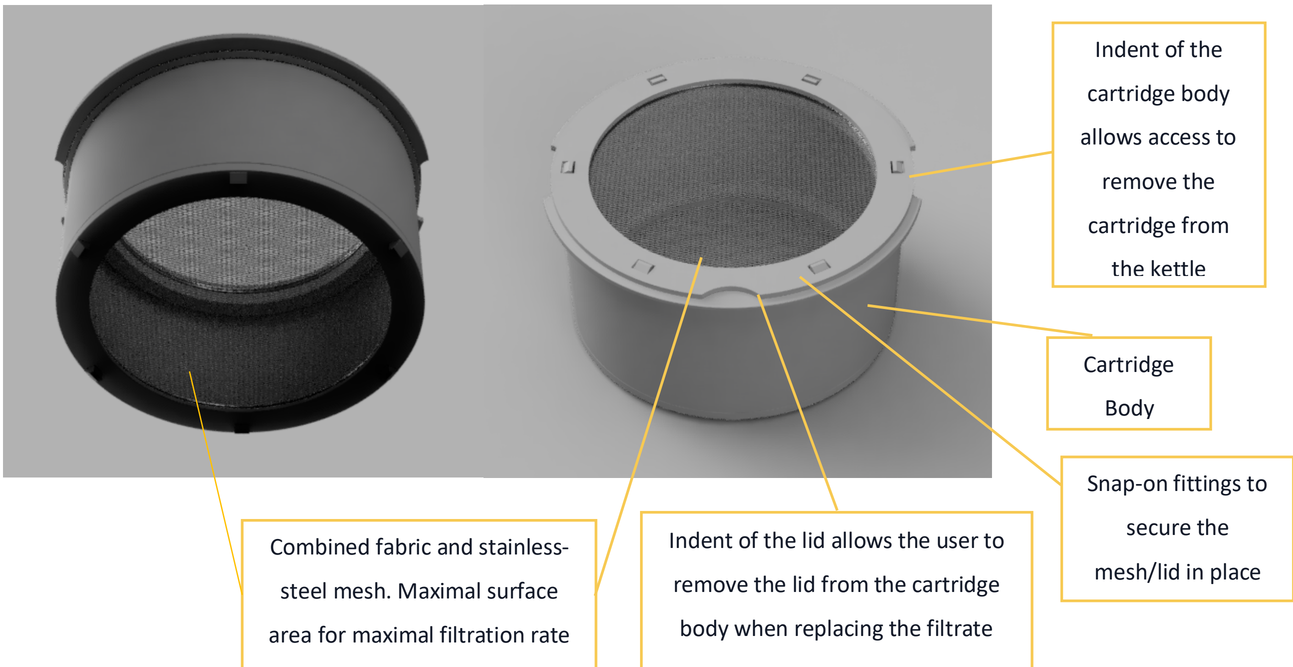


Figure 33 – Final CAD of the filter cartridge

2.8.1 Filtration structure summary

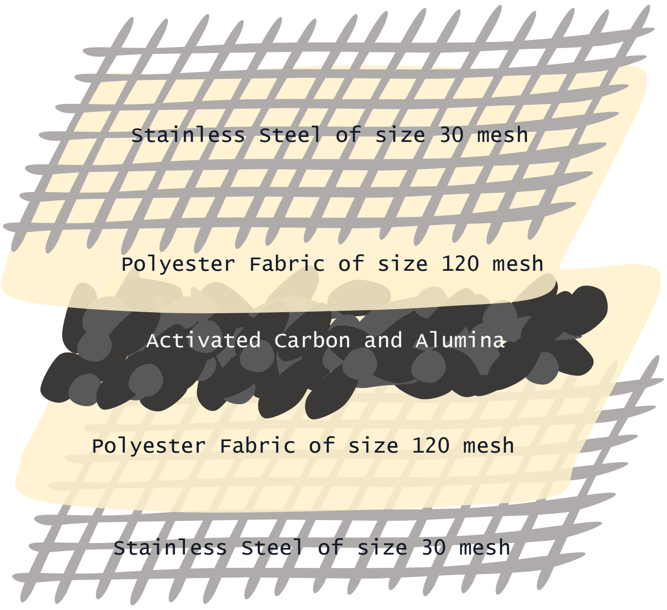


Figure 34 – Illustration summarising the layers of the final filter design.

The filtration system is summarised by Figure 34. Using two mesh discs provides additional purification of water upon entrance to the boiling region. Finer filtrate such as sand can be added by the user to improve filtration quality if they desired so.

2.8.2 Mesh Disc

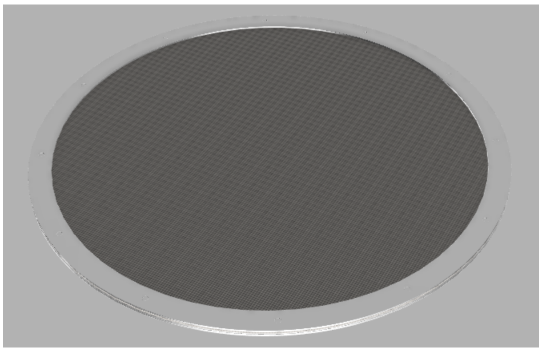


Figure 35 – A coffee AeroPress reusable filter, left, inspiring the mesh disc filter piece, right, for the water filter.

The coffee AeroPress filter inspired the mesh disc which appears at the top and bottom of the filter cartridge. A stainless-steel sheet is pressed along the rim sandwiching the stainless steel and polyester meshes together.

2.8.3 Assembly Diagram

A functional assembly diagram consisting of an exploded view of the filter cartridge is show in Figure 36. Snap locks have been used between the cartridge body and the cartridge bottom, and also embedded in the filter lid, both holding a mesh disc in place. This allows the mesh disc to be removed and rinsed when necessary.

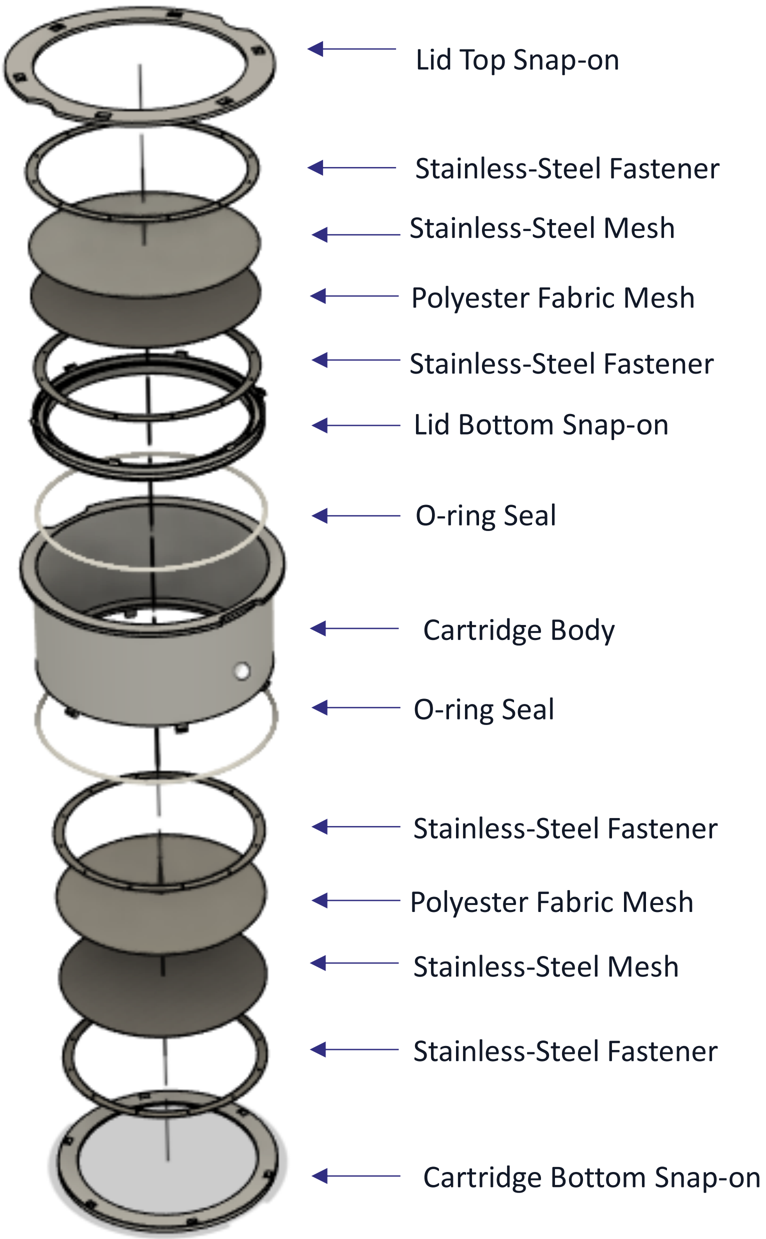


Figure 36 – Exploded view of the filter cartridge assembly, labelled with each part.

Tolerancing has been applied to dimensions with contact of other interfaces such that holes will always be bigger than any inserts. This ensures snap hooks fit into their associated holes.

2.9 Technical Analysis

2.9.1 Heat Transfer Model

A steady state heat transfer analysis was executed on the filter cartridge. Convection of steam at 100◦C of convection coefficient 100W/m^{2}K was applied to the stainless-steel mesh at the bottom of the filter [26]. Convection of ambient air at 20◦C with a coefficient of 10W/m^{2}K was applied to the remaining external faces [27]. Conduction was assumed negligible as the polypropylene has high insulation with non-polypropylene/silicone materials in the mesh disc.

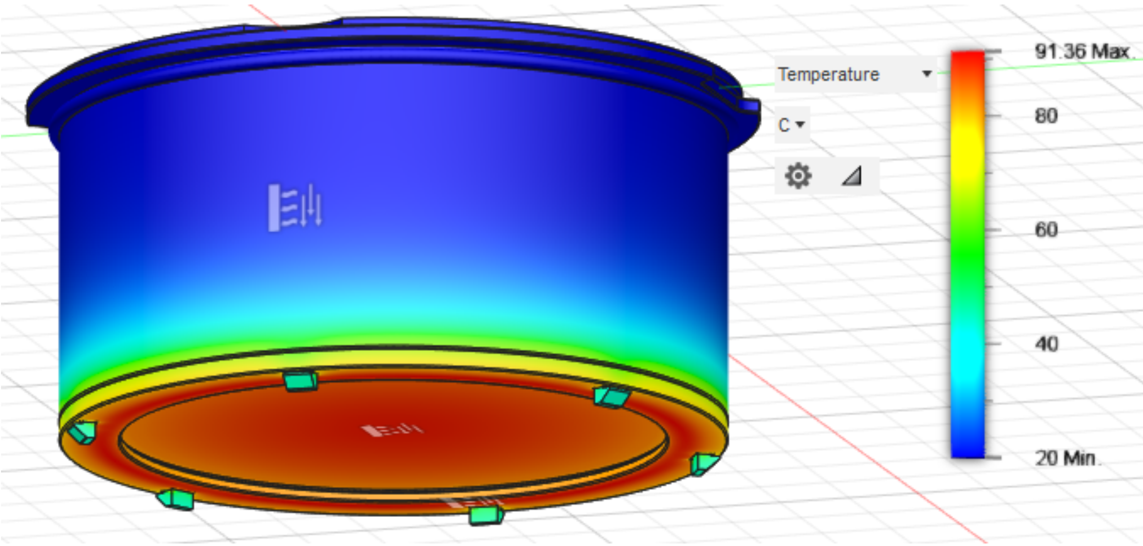


Figure 37 - Thermal Convection simulation of the filter cartridge assembly using Fusion 360. 100◦C boundary condition of convection applied to the bottom of the filter. 20◦C boundary condition applied to remaining external faces of the filter.

From modelling a convection only simulation, it is denoted that the cartridge body does not reach above 70◦C. However, although the maximum recommended operating temperature is 82.2◦C for polypropylene, it is expected to reach above 80◦C temporarily and so will not be able to exhibit much deformation. The cartridge bottom snap on component could alternatively be made of a more heat resistant material to reduce the risks of cartridge deformation. The moulding temperature of polypropylene is above 200◦C, so will not deform under the kettles highest operating temperature of 100◦C [28]. These results are an overestimation as steam will condense upon contact with the cartridge and provide a film of insulation.

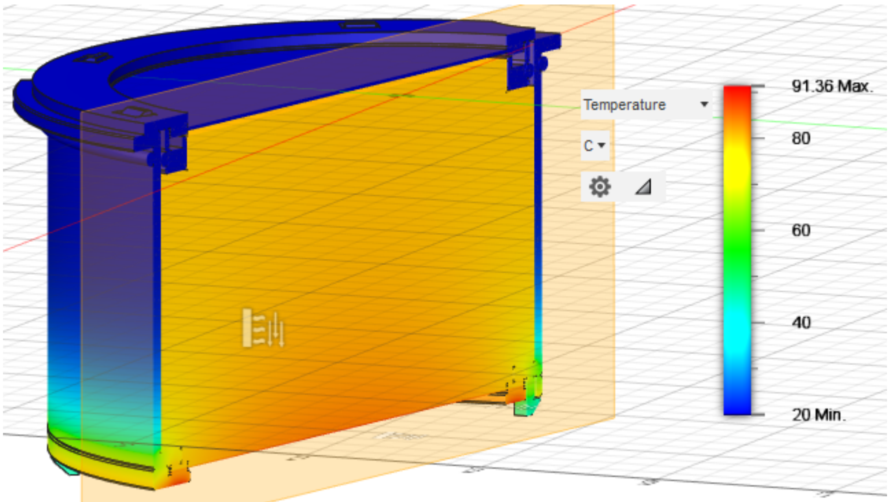


Figure 38 - A section view of the heat transfer results, showing the activated carbon and alumina mixture reaches around 80◦C.

Activated carbon release adsorbed metals at 500 - 900 ◦C [29]. This is 300 - 4000 ◦C for activated alumina [30]. The modelled temperatures for all materials are safe for use in a kettle. The cartridge top and body reaches less than 30◦C, sustaining user safety when handling straight after boiling water.

2.9.2 Filtration Time

In reference to the experimental prototyping on page 29, 10 seconds for 250ml to pass an 80mm diameter of fabric mesh deems a reasonable estimate perhaps adding 5 seconds with additional fabric layers and the activated filtrate contributing negligible difference to filtration. For filtering 750ml, the capacity of water above the filter, this could be around 45 seconds to filter through two polyester textiles of an 80mm diameter entrance and a 45mm thickness of activated carbon and alumina. This is will meet the filtration time specification of under 60 seconds. The BRITA filters take longer (70 seconds) because of having two 18mm diameter plastic meshes with their cartridge body of 0.1mm fine gaps. On the other hand, maximising the mesh area will allow greater filtration flow rate with dense packing of activated filtrate flourishing greater purification quality.

Figure 39 - The bottom of a BRITA MAXTRA filter.

2.10 Application of Technology

The filter cartridge will sit housed in the upper region of the kettle by a flange. An indent accessible from the entrance of the kettle lid will allow the filter to be lifted and removed from its press fit position. An indent for the removal of the mesh disc is also present on the filter lid. Rubber silicone seals prevent unfiltered water from passing around the filter without entering through the mesh disc, a key specification.

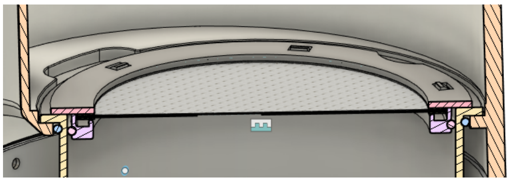


Figure 40 - Filter cartridge section view whilst housed in the kettle.

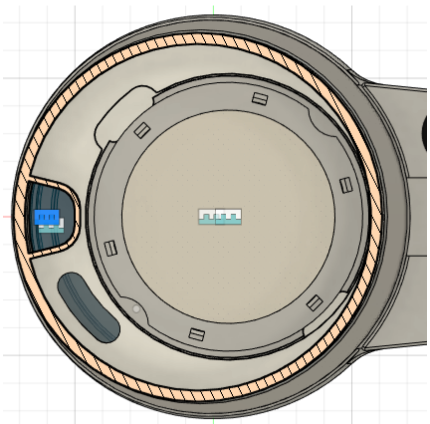


Figure 41 - Top view of the filter cartridge whilst housed in the kettle.

2.10.1 Design risks

Table 12 - Risk Assessment/DFMEA for the filter cartridge.

	Risks	**Likelihood (1-5)**	**Consequence (1-5)**	**Overall Risk (1-25)**	**Risk Level**	**Mitigation**
1	Poor tolerance accuracy	1	5	5	Medium	Redesign injection moulds or specify tolerances on more dimensions. These may need to be tighter.
2	Incorrect mesh orientation by user	4	2	8	Medium	Provide guidance in an instruction manual.
3	Insufficient packing density of carbon and alumina	3	5	15	High	We should supply more filtrate than needed to ensure packing is optimised.
4	Leakage of filtrate into water	1	3	3	Low	All openings must be of smaller size of an estimated piece of alumina or carbon.
5	Polypropylene parts break	2	4	8	Medium	The filter is not designed for large stresses in usage, with affordability being a driving factor in the design. Replaceable parts are offered in case of fatigue.
6	Mesh disc breaks	1	4	4	Low	The stainless-steel fastener gives the fabric mesh a rigid form to ensure the fabric does not become crimpled. Replacement mesh discs are offered for purchase as they cannot be amended.
7	Lid difficult to remove	1	4	4	Low	An indented ridge allows users to remove the cartridge and lid.

The risk assessment highlights the highest risk, risk 3, where loose filtrate packing can allow water molecules to be poorly exposed to the filtrate and ineffectively remove harmful contaminants. This is the highest risk as activated carbon and alumina are the main contributors in removing dissolved contaminants and reducing turbidity. With loose packing, chemical purification will not be optimal. The remaining risks are not health concerning but are undesirable in terms of interactions between parts which can affect the lifetime of the filter cartridge.

2.10.2 Costs

The complete cartridge piece will cost a total of £2.84 in raw materials. The activated carbon and alumina filtrate will cost an additional 9p for each 150g of refill, consisting of 100g of activated carbon and 50g of activated alumina. A complete breakdown of calculations can be found in the Appendix D.

2.10.3 Manufacturing

The propylene cartridge parts are injection moulded, a common method for moulding polypropylene. The cartridge should classify as small, so the moulds should cost between $1000 and $5000 (£700 to £3500). A single injection moulding machine can process all polypropylene parts of the kettle, costing around £5000.

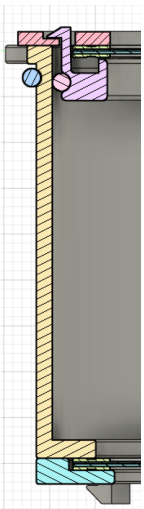


Figure 42 - A cross section of the filter cartridge, featuring a focus on the shape for manufacturing considerations.

The form of the injection moulded parts has been designed for easy removal of parts from their mould, where parts can easily be removed from two sides of a mould, using rounded edges for assistance. Though tapers could also assist, they have not been used, to maximise filtrate space. The silicone rubber O-rings are purchased from external manufacturers as these are not bespoke parts.

The layers of the mesh disc are individually purchased and can be cut and pressed together simultaneously by a specially designed machine. This will press the 4 layers together, deforming the metal sheet. It will then cut through the polyester fabric, stainless-steel mesh, and stainless-steel sheets into circles with an 85mm diameter, whilst being clamped together in a pressed sheet. The stainless-steel sheet will require an internal circle of 77mm diameter to be cut out also which will be cut prematurely to the press and cut process. This is demonstrated by an illustration in Figure 43.

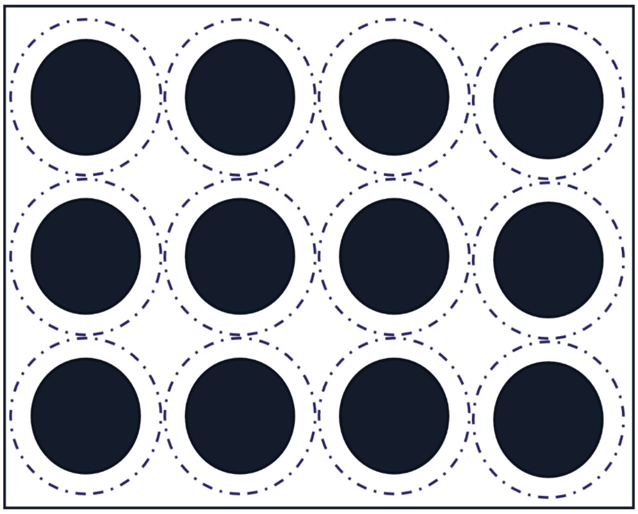


Figure 43 – An example of the mesh discs manufacturing schematic. Stainless-steel sheet with 77mm diameters circles removed (black filled circles). Dotted lines represent cutting of the mesh discs.

2.10.4 Supply chain

Throughout the operational life of the kettle, the filtrate will need replacement weekly. Due to the rural environment of our users, replacement supply through distributors can reasonably deliver every 3 months, supplying 1.8kg of filtrate.

2.10.5 Lifecycle

2.10.5.1 Activated Carbon and Alumina

An agreement can be made with a specialist activated carbon and alumina company based in Kenya, where more than 7 are based in Kenya, to collect and redeliver the activated filtrate [31]. Activated carbon can be reactivated when heated between 500 - 900 ∘C [29]. Activated alumina is reactivated at 300 - 4000 ∘C [30]. Activated carbon and alumina will not release adsorbed toxic chemicals unless heated to these temperatures, therefore, will not be hazardous in the environment and can be disposed of with general waste.

2.10.5.2 Polypropylene Parts

The cartridge casing components made from polypropylene are recyclable. All parts will be engraved with the recycle symbol encasing “5” for the associate material. The recyclability of this product is determined by whether users have access to recycling collection points so it is possible these parts could end up in landfill. If so, it will take 20 to 30 years to biodegrade and will be an unsustainable disposal method [32]. It does not leak toxic chemicals and is an environmentally safer plastic compared to most, such as PVC. Due to the quantity of rural Kenyan residents, only 15% of plastic waste is recycled [33]. For those who have communal recycling facilities, the propylene can be recycled back into pellets and remoulded into useful products, such as another filter cartridge, plastic bottles, Tupperware and chairs.

2.10.5.3 Silicone rubber O-rings

Although silicone can be recycled, it is likely to be thrown away as only specialist recycling facilities can recycle silicone [34]. When recycled, they can be downcycled into industrial lubricant or playground mulch [34]. It will take 20 years to degrade in landfill [35].

2.10.5.4 Maintenance

Although the mesh layers can be reused, once the mesh discs are separated, the outer pressed sheet cannot be reused. This is due to the press process requiring deformation of the metal sheet to hold the layers together. Reuse of this part will mean the mesh layers will not hold together well. It is recommended the meshes are cleaned frequently to reduce the damage that gravel may elicit and prolong the life of the mesh discs.

2.11 Conclusion

The filter made of a polypropylene casing will secure mesh discs with snap fittings. The mesh discs compose of the stainless steel 304 mesh of size 30-mesh and a 120-mesh textile of polyester. A heat transfer simulation illustrated the safe selection of materials for user interaction and from chemical alterations. The low costing specification has been met where the cartridge unit will cost £2.84 per unit, with filtrate refills costing an additional 9p. An improvement in the design would be to include another seal along the inner cartridge bottom where there is an opening from the bottom cartridge snap fitted piece. This will ensure water passes through the mesh. Although calculations were conducted for the amount of filtrate required, it would be desirable to have expertise assistance with how frequently the filtrate would need to be replaced as it was scaled based BRITA's information, filtering 100L for 4 weeks. It was found that 100g of activated carbon with 50g of activated alumina would be necessary to filter typical natural water in Kenya, requiring a weekly replacement of filtrate lasting 16.7L of water. Research into whether zeolite's adsorption properties is more effective than activated carbon and alumina could have been conducted to determine whether the risks of using zeolite would outweigh the benefits of not having to replace the filtrate every week. Filtration has been estimated to around 45 seconds to pass 750ml of water through. Experimental prototyping has assisted confidence in quick filtration times, whilst purification quality has been based on research conducted during the TFS. For improvement, a more accurate filtration time could be calculated with a physical prototyped filter cartridge. This is also applicable for water quality. In the future, with access to 3D printing, accurate Kenyan water samples and a TDS meter, the effectiveness of the filter could be understood and designed with greater confidence in purification. As a mechanical engineer, the filter design introduced some technical challenges in calculating the amount of filtrate required and filtration times. The maximum temperatures of the cartridge from simulating a convective heat transfer model with 100◦C steam was around 85◦C. This model overestimates temperature results, as steam will condense along the bottom of the cartridge, providing some insulation. Improved thermal modelling could be conducted by simulating a transient model with modelling radiation and conduction. If time permitted, improved sustainable sourcing of materials (polypropylene, activated alumina and activated carbon) at optimal costs could be sourced to keep the product in line with some of the SDGs where the design of the product has been oriented towards sustainability.

3 Top Casing

3.1 Summary

The aim of this section was to create a low-cost top casing that maximises functionality. The selected material used to build most of the components in this sub-assembly is polypropylene, which is ideal for injection moulding.

Testing on similar products was carried out to inspire the design of the optimum spout, latch, and hinge mechanisms; this was combined with unique concepts to produce the final product. The design underwent a significant number of changes and version updates to improve manufacturability including the addition of pass-through coring and ribs to injection moulded parts.

The total polypropylene material cost is £0.70/unit with £29,000 for the injection moulds. The three required springs will be custom made with 0.1 Nm of torque for the hinge torsion springs and cost under £0.03/each.

Though considerations were outlined to improve the design for more efficient manufacturing and improved functionality, it was concluded that the majority of the design specification categories were adequately met with a functional design that prioritised the user's experience.

3.2 Introduction

The aim of this sub-assembly is to create a low-cost top casing with maximum functionality. The objectives set to complete this aim are:

- To keep the customer in mind throughout the design
- Optimise parts for manufacture
- Define a list of acceptable parameters to measure the design's success

The top casing sub-assembly is the section of the kettle that is most interacted with by the user; it is where the water is poured in and where the water pours out, so any design decisions made for this sub-assembly start with the end user. An overview of the design process used for the sub-assembly is shown in Figure 44.

Figure 44 - Design process flow chart for top casing sub-assembly

3.2.1.1 Design Considerations & Requirements

Phase 01 of the design process chart in Figure 44 was explored and detailed in 'G06 VoC Presentation' and 'Ktembo Business Report'. Phase 02 of the design process and additional design specifications are outlined in Table 13.

Category	Requirement	Lower Limit	Upper Limit
Volume	A third of the lower boiling section's volume.	A quarter	Equal
Ergonomics	To be as comfortable and accessible as possible within reason.	Easy to operate with two hands.	Operable with one hand by a customer with limited dexterity.
Efficiency	Minimise heat loss from the lower boiling half.	No insulative properties.	As insulated as the bottom half.
Safety	Make suitable provisions to reduce any possible risk.	Mitigate major risks to user safety.	Remove risk of burns, water spillage (into electrical systems), all other possible injuries.
User Error	Reduce the possibility of user error.	Design may be significantly cheaper, more reliable, or more efficient at the expense of possible misuse of the product. In this eventuality, detailed user instructions	Eliminate all possibility for human error.

		should be provided along with user testing.	
Cost	Must be low to allow low sale price and affordability for target market.	Minimise without sacrificing functionality.	£3 – though this figure will be dependent on the cost of other sub-assemblies.

Table 13 – Targets to consider for this design with the minimum acceptable solution and maximum reasonable solution

3.3 Ideas and Concepts

The key, encompassing function of the top casing is to separate the flow of dirty water going in and clean water leaving the kettle to avoid contamination of the filtered, boiled water. This requirement dictates the overall shape of the casing and therefore all other sub-components must be designed after the casing with compatibility in mind. Rudimentary sketches of the overall design were made (example sketches: Figure 45) to visualise the concept and spot any potential problems before progressing to the prototyping phase.

Concepts were also sketched for the latch mechanism; all sketched ideas were original and existing products were not analysed until a later stage so as not impede creativity in concept generation.

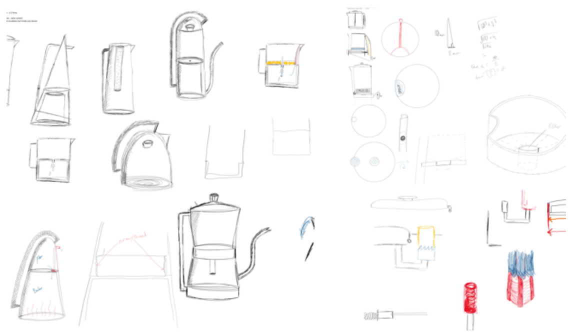


Figure 45 – Examples of concept sketches

3.4 Prototype

Though the sketches provided a useful creative platform to quickly visualise which concepts would not be feasible either physically or financially, it is often the case that any potential issues are not immediately obvious until a more detailed CAD model is drafted.

3.4.1 Top Casing

The top casing was created as a basis for all of its constituent components (Figure 46), the design was simple as the initial intention was to use stainless steel 304 for the main body for improved sustainability and perceived quality. However, after considering the necessary fixturing to join the top and bottom casings, the filter casing, the hinge mechanism and lid, etc. the design became significantly more complex (Figure 47). Before developing the design, it was important to establish what material and manufacturing process would be used to understand what features would be possible and design for manufacture, this is discussed in Section 3.5.1.

Figure 46 – Original top casing design

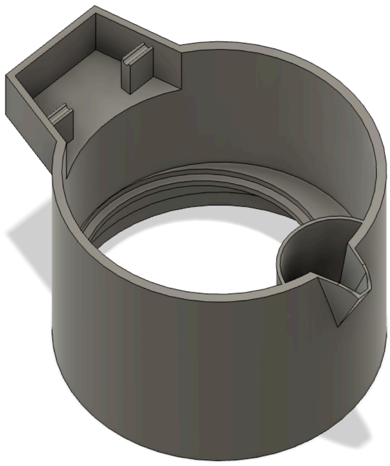


Figure 47 – Further developed top casing design

3.4.2 Latch/Hinge Mechanism

In addition to the concepts generated in Phase 03 of the design process a range of mechanisms from existing products on the market were analysed to draw inspiration from (Table 14).

Product	Hinge Complexity	Latch Complexity	Ergonomics of Latch Release	Number of Directional Translations
Cuisinart CPK-17	2	4	4	4
Breville KE700BSS	4	4	4	4
Breville Curve	0	0	1	-
Thermos Lid	-	2	2	2
Vektra Vacuum Kettle	1	? – Could not open up without breaking.	4	? – Could not open up without breaking.

Table 14 – table assessing the various chosen product lids with regards to their complexity, ergonomics of where the latch release button is and the number of directional translations from button to latch (i.e. if the mechanism translates vertical input into horizontal motion directly that would be 2 directional translations)

The Cuisinart CPK-17 and Breville KE700BSS use similar latch mechanisms that translate vertical motion of the button being pressed into horizontal, however the horizontal motion is in the incorrect direction, so a spring-loaded rotational hinge is used to reverse the direction. The Cuisinart's hinge system uses a set of torsion springs and a simple rubberised hinge to dampen the opening motion with friction. However, the opening motion was not consistent and sometimes the rubber would have minimal damping effect. The Breville KE700BSS used a more complex gear arrangements (Figure 48) to give consistent damping that is less likely to degrade over time.

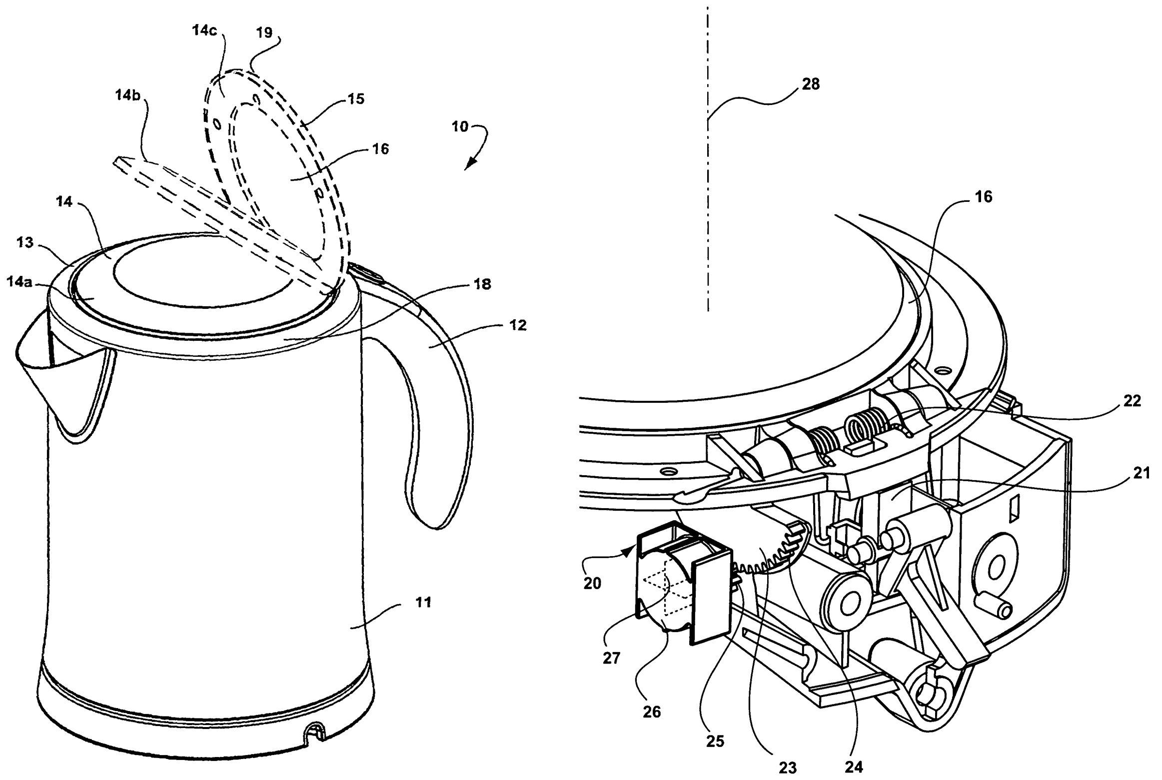


Figure 48 – Patent image of the Breville KE700BSS hinge damping system [36]

The Breville Curve has a simple lid that can be removed as a separate component, which despite its simplicity and inherent robustness, performs poorly ergonomically as it requires the user to have two hands free and for the kettle to ideally be on a flat surface. This type of lid may be implemented in a future design depending on customer feedback and future user studies.

The Thermos lid is unique in the list as it can be set to either an open or closed position at the click of a button, the mechanism used is similar to what can be found in a mechanical pen. One of the concepts created involved using this as a latch release and the mechanism was modelled in Fusion 360 (Figure 49).

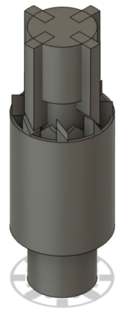


Figure 49 – Mechanism similar to what is found in retractable pens and Thermos lids modelled in Fusion 360.

The Vektra Vacuum Kettle's latch mechanism was sealed in the lid and not accessible, however the hinge mechanism was visible and does not appear to use any damping for the torsion spring-loaded hinge. This did not affect the perceived quality of the product and did not inhibit the functionality of the kettle and was therefore selected as the chose hinge design.

It was decided that the Cuisinart CPK-17's latch mechanism would be the most suitable for our design. However, after modelling a similar mechanism in Fusion 360 it was clear that the design was more complex than anticipated as it required more movement translations (vertical to horizontal, rotational to linear) than necessary and constraining each movement was unnecessarily complicated. A simpler alternative with fewer parts and less movement translation was created instead; the design uses a simple vertical to horizontal pivot link which allows the user's button push to pull a series of spring-loaded flat brackets fixed to the latch releasing the lid so the spring-loaded hinge can open it (Figure 50 and Figure 51). Another advantage to this system is that there is no risk of patent infringement as it is an original idea.

Figure 50 – Rendering of the latch mechanism. The parts are coloured to distinguish between them, in reality the only coloured part would be the button

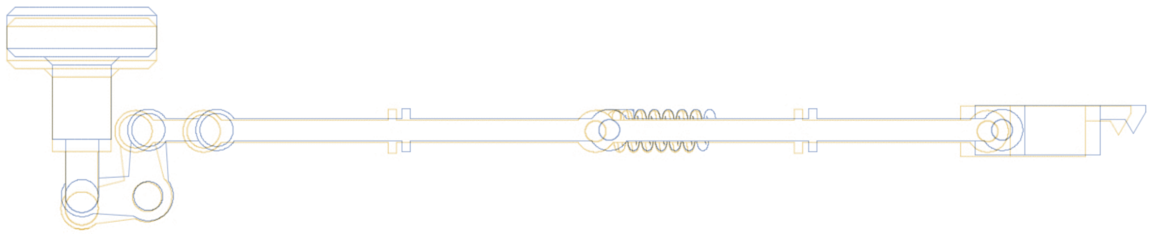


Figure 51 – Range of motion of the mechanism where yellow is the latch in its open position

3.4.3 Spout

The original design (Figure 52) for the spout was optimised for smooth pouring, reducing surface tension of the water as it leaves the spout. The design was modelled from measurements taken from various successful spouts (Table 15) and theories of cohesion and adhesion of water as its poured; if the angle between the spout exit and the vertical direction is too small, there will be adhesion of the water molecules to the kettles surface, the speed at which the water leaves the spout is also important so the angle from the casing to the spout is also a factor [37].

As there are so many factors involved it is hard to design an original spout without adequate testing. So existing spouts were tested to find the most successful spout and use it as the basis for the design, the results are in Table 15.

Product	Shape Complexity	Slow Pour Quality	Quick Pour Quality
Cuisinart CPK-17	3	3	4
Breville KE700BSS	2	3	4
Breville Curve	2	4	5
Vektra Vacuum Kettle	1	3	4
Bialetti Moka Pot	4	5	5

Table 15 – Scores out of 5 where a lower score means there was more water adhesion to the spout of the kettle in a given pouring scenario

The Bialetti Moka Pot had the most successful pour and did not adhere to the surface at all pour speeds. Consequently, it was selected as the optimum design and the Moka Pot was measured using vernier callipers and modelled on CAD (Figure 52).

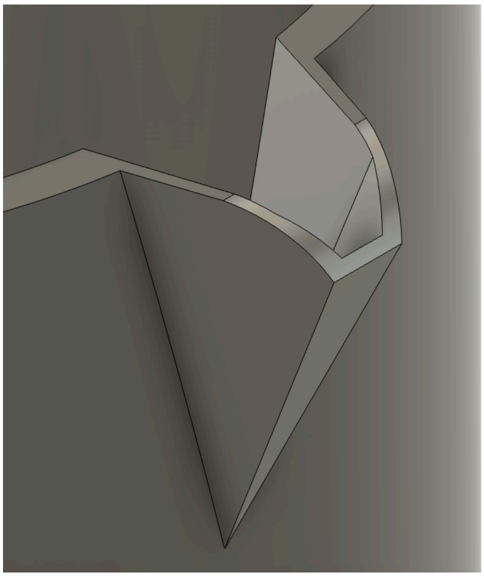


Figure 52 – Fusion 360 model of spout measured from Bialetti Moka Pot

3.4.4 Valve

To limit heat loss from the spout during boiling it was important to find a solution to seal the exit and also incorporate a pressure release valve. A number of options were considered that fall into two categories:

1. Manually operated valve that opens with a button (similar to the Vektra Vacuum Kettle).
2. Automatic valve that requires no user input (ball valve).

The advantage to the manually operated valve is that once open, flow is not constricted, and a good flow rate can be achieved when pouring water. Conversely the ball valve restricts flow but eliminates the risk of human error (leaving the valve open during boiling and therefore reducing efficiency, forgetting to open during pouring). After brainstorming concepts for manually operated valve mechanisms it was clear that it would have furthered the complexity of the design and with the risk of user error in mind (and returning to Phases 01 and 02) it was decided to implement a ball valve (Figure 53) in the lower section of the spout funnel (Figure 54).

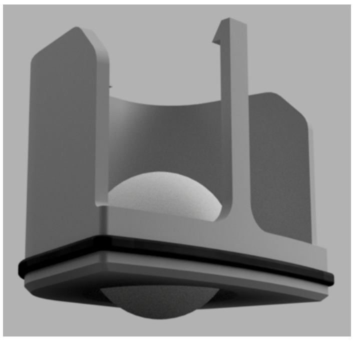


Figure 53 – CAD model of ball valve

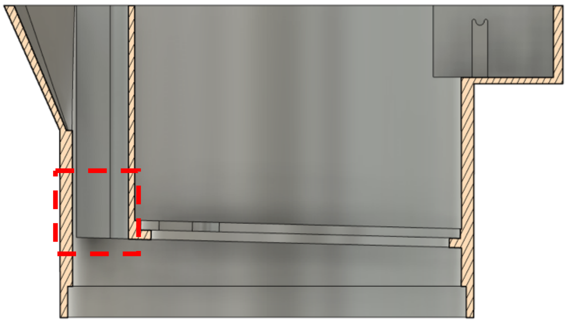


Figure 54 – Top casing where the red square indicates the intended valve location

However, while brainstorming possible sources of user error, the issue of over-filling the boiling section of the kettle arose. Due to the insulation on the lower section, it was deemed unfeasible to install a Perspex window in the insulation and so the solution had to be built into the top casing. The proposed solution was to use the spout funnel to view the water level, however with the ball valve installed this would not be possible. To solve this, it was proposed that the valve be installed on the front end of the lid so when the lid is up for filling, the funnel is clear for viewing.

The issue with the valve fixed in the lid is that with the current spout design, heat would be allowed to escape (Figure 57) and creating a valve that sits deeper into the funnel would not allow the lid to open. The spout design had to be changed to accommodate the valve and allow the lid to open, after a number of iterations the spout in Figure 56 and Figure 58 was created. The design differs from all those in Table 15 and so a cardboard model shown in Figure 59 was made to test water flow and ensure it poured well. The results are shown in Table 16 so they can be directly compared with the results from Table 15.

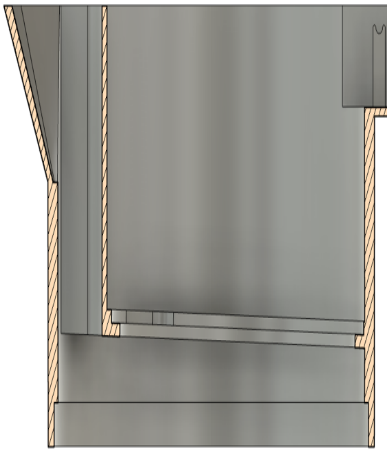


Figure 55 – Original spout design

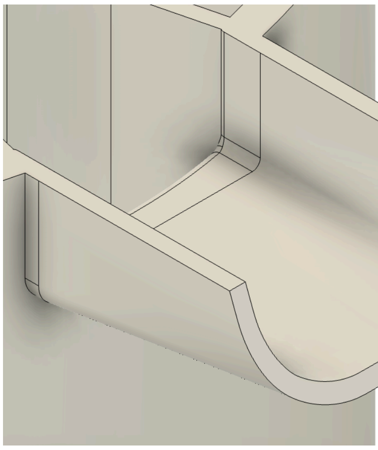


Figure 56 – Updated spout design to accommodate ball valve

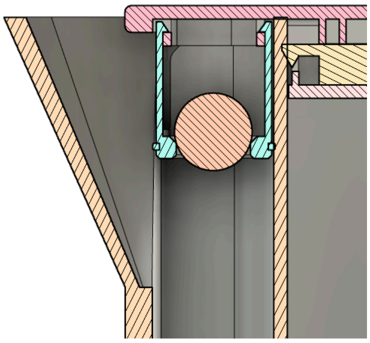


Figure 57 – Cross-section of ball valve and original spout

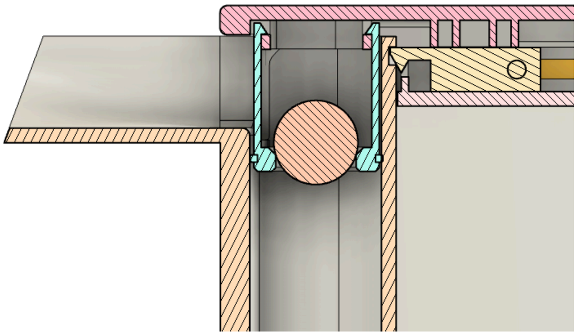


Figure 58 – Cross-section of ball valve and updated spout

Figure 59 – Cardboard model of updated spout

Product	Shape Complexity	Slow Pour Quality	Quick Pour Quality
Cardboard Prototype	1	3	4

Table 16 – Pour testing results for cardboard prototype

3.5 Design for Manufacture

3.5.1 Material

Before adjusting the design to reduce cost and improve manufacturability a suitable material must be selected. When considering the choice of material for the top half, the following factors had to be accounted for:

- Ease of manufacture
- Thermal properties
- Food grade
- Environmental impact
- Cost

Due to the growing complexity of the design, it was decided that a plastic upper casing would be the most suitable solution as it is the easiest and cheapest material to manufacture. Using a combination of materials was considered (for example: a stainless-steel 304 casing with a polypropylene lid and mechanisms) but fixing of metal and plastic composites would add complexity to the sub-assembly that outweighs the possible environmental and thermal benefits of using a composite design.

The most commonly used plastic in kettle production is polypropylene due to its physical properties, namely:

- Its thermal behaviour when melted for injection moulding.
- It is almost entirely impermeable, so no further waterproofing is needed.
- Unlike other plastics, polypropylene does not chemically leak.
- It is highly malleable when subjected to bending and can withstand repetitive deformations which could prove useful in the mechanisms' designs.

However, untreated polypropylene can be subject to degradation at temperatures over 90°C; manufacturers can avoid this by adding polymer stabilisers to allow the material to withstand higher temperatures.

Though Kenya has a multitude of plastic injection moulding facilities it is not clear whether they are suitably equipped for our purposes. The location will therefore need to be researched and discussed further.

3.5.2 Design Iterations

After establishing polypropylene as the chosen material, the designs could be adjusted for improved manufacturing. This sub-section will discuss any changes that were made to decrease manufacturing cost and material usage.

3.5.2.1 Casing

The top casing was designed so it can be moulded in a single operation with as few side features as possible to reduce post-processing work after injection moulding, some features were unavoidable or more convenient than alternative options, such as the rivet holes at the bottom to fix the top and bottom halves together. The mould would be split as in Figure 60 with the cavity below the parting line (illustrated in red) and the core for all features above the line. The features are at an angle to compensate for the angle of the kettle's base.

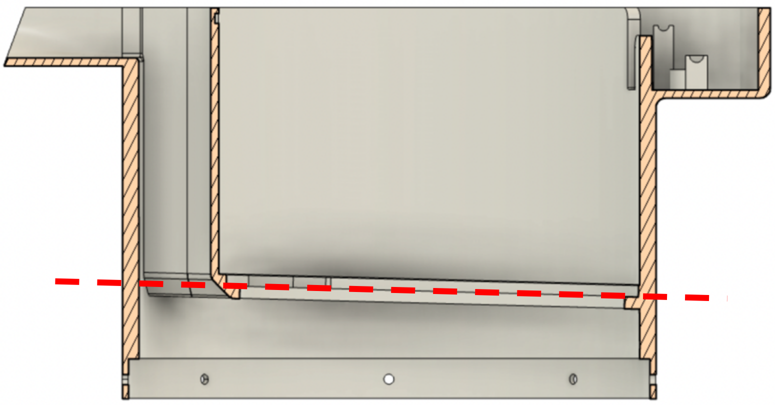


Figure 60 – Top casing with illustrated injection mould parting line

3.5.2.2

If future adjustments could be made, draft angles should be added to all vertical surfaces to allow the part to be removed from the injection mould easier, angles would be opposing on each side of the parting line as in Figure 61. And all dimensions can be increased in size by a factor of 0.4% to account for shrinkage [38]

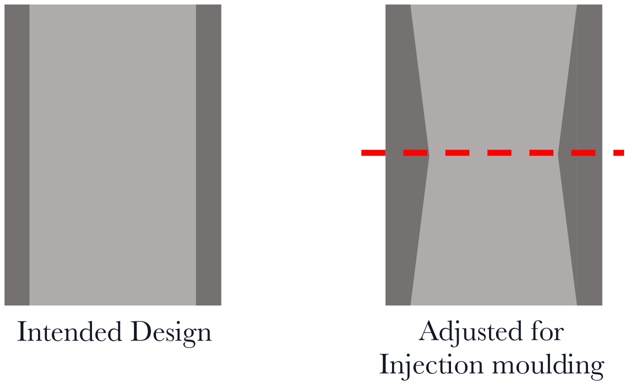


Figure 61 – Simplified figure illustrating draft angles to optimise removal from mould.

3.5.2.3 Latch Mechanisms

The latch mechanism discussed in Section 3.4.2 originally had the button in a higher position with the joint extending backwards as in Figure 62. Though this would function as intended it meant that the casing had to extend further back and upwards affecting ergonomics and increasing the quantity of polypropylene required. The joint was rotated to use the space more efficiently whilst still maintain sufficient range of motion to operate the latch as illustrated in Figure 51.

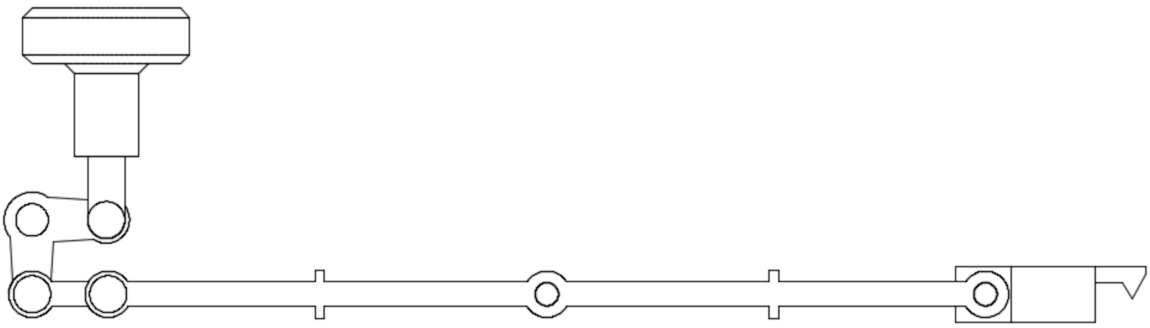


Figure 62 – Drawing of original latch mechanism design

The latch itself also underwent a few iterations; the first was intended for a single operation injection mould with a complex core side and simple cavity with pass-through coring (explained in Section 3.5.2.4, the design is shown in Figure 63. The design was then simplified (Figure 64). However, a few small changes would have made the design more suitable for injection moulding, these changes are illustrated in Figure 65 and Figure 66.

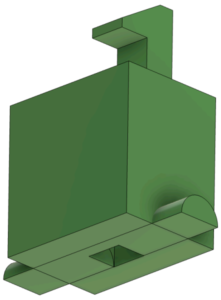


Figure 63 – Latch design with pass-through moulding

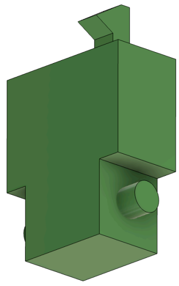


Figure 64 – Updated latch design

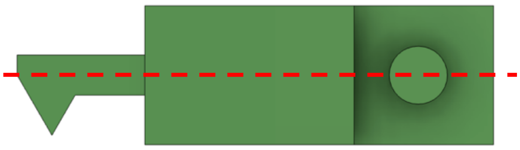


Figure 65 – Updated Latch design showing parting line for simple injection moulding

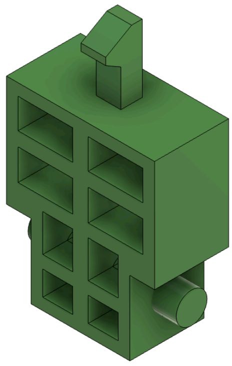


Figure 66 – Updated Latch design with ribs to reduce material usage and maintain strength

3.5.2.4 Lid

The lid was designed primarily for functionality and adapted for manufacture after. The key adjustment was to add ribs to the thin areas to add strength and rigidity, this can be seen in Figure 67.

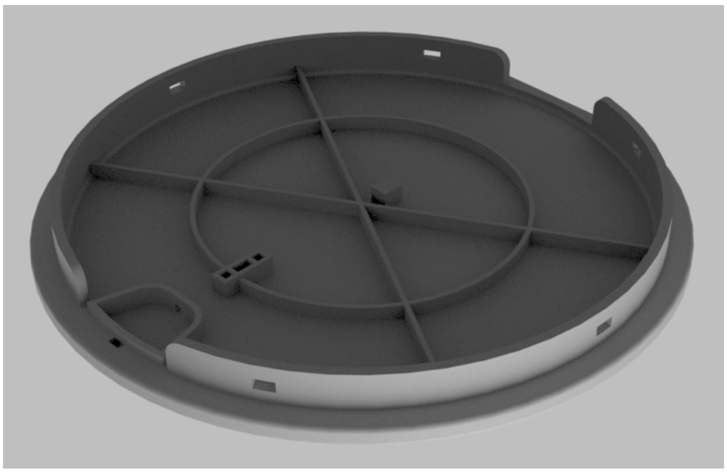


Figure 67 – Lid top with additional ribs for rigidity

However, upon reflection it was clear that parts of the design could be adapted with minimal to no change in functionality to reduce manufacturing cost. The first change was to introduce pass through coring to the latches found in the lid, this change is best illustrated in Figure 69 and Figure 70, in Figure 69 an additional 'slide' would be required to be removed before the part can be removed from the mould. In Figure 70 the additional slot would allow the cavity of the mould to have a protruding feature to create the undercut.

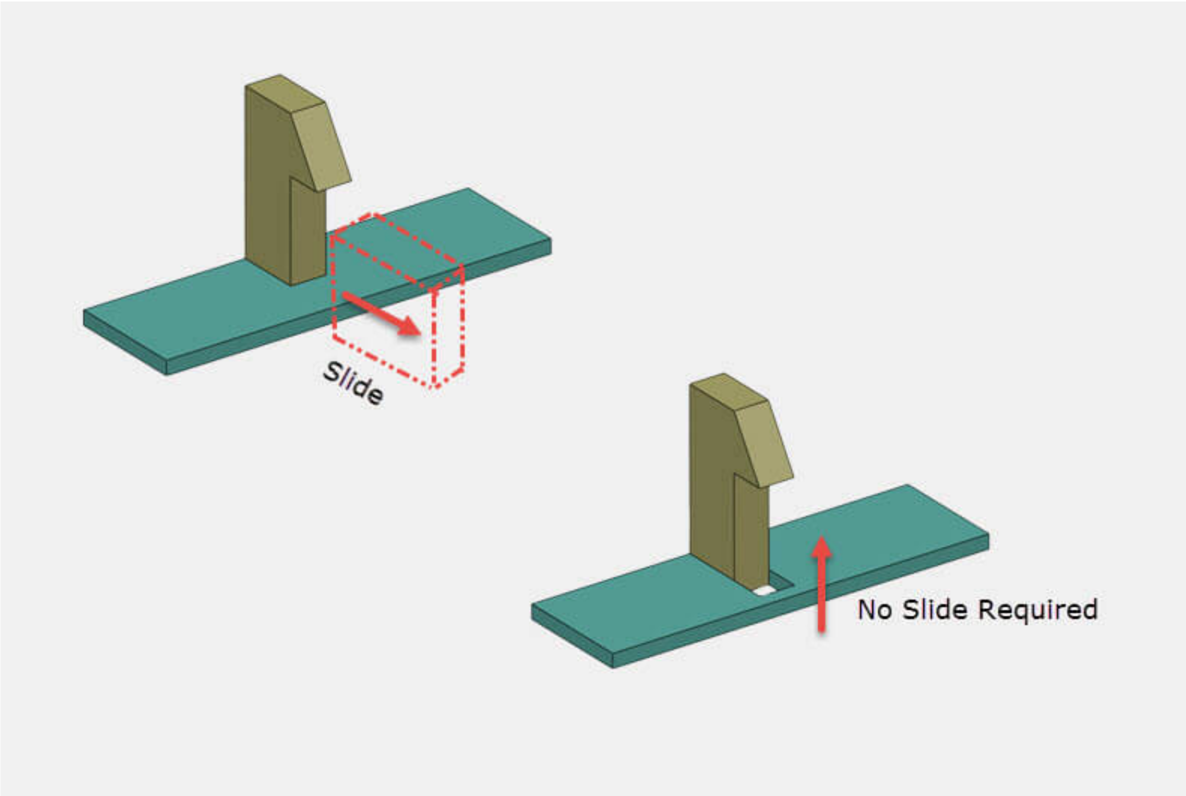


Figure 68 - Illustration of a latch with simple pass-through coring [39]

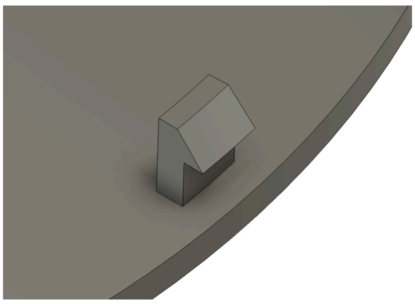


Figure 69 – Original latch design

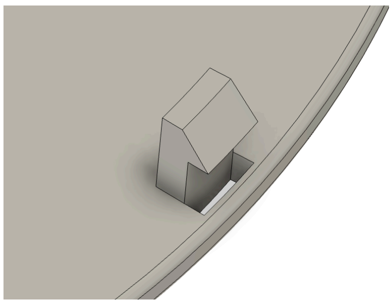


Figure 70 – Updated design for improve manufacturability

3.6 Cost

There are two main costs associated with the top casing: material cost and manufacturing/tooling cost. The total material cost is an estimated £0.70 for the 235 g of polypropylene required.

The main expense comes from tooling, as complexity increases, so does the tooling cost; All small parts can be injection moulded in one operation with a single tailor-made tool at an estimated cost of £9,500, the top casing itself is more complex and due to its larger size, the tool would cost an estimated £20,000. Tooling cost totals an estimated £29,500.

Additionally, there are three springs in the design: one for the latch mechanism and two for the hinge. A tension spring with a full loop on each end (Figure 71) and two symmetrical torsion springs with the torque required to open the lid (Figure 72). The required torque to open the lid from the hinge is approximately 0.17 Nm so each torsion spring should have at least 0.1 Nm. From online stores each spring can be bought for less than £0.03 [40, 41, 42].

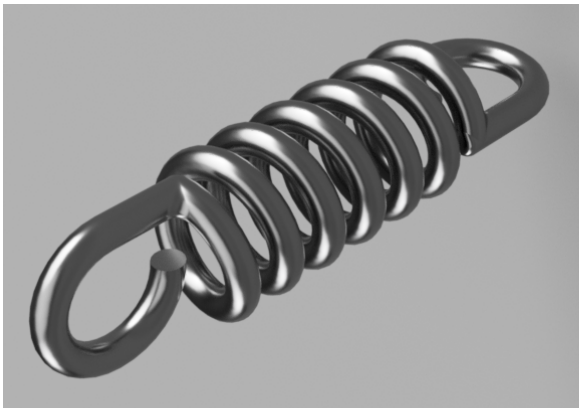


Figure 71 – Latch mechanism tension spring

Figure 72 – Hinge mechanism torsion spring (>=0.1 Nm)

3.6.1.1 Costing limitations

In reality there would be a significant number of factors influencing cost that are difficult to assess until manufacturing commences. For example, transportation from the country of origin could be significant if manufacturing does not take place in Kenya.

The estimated material mass may differ with the sprue and wasted material/faulty parts.

Quotes for other manufacturing costs such as labour and machine time were not available which would be a significant addition to the total.

3.7 Product Lifecycle

With a product that has the potential to save many lives it is important to assess and weigh the benefits of a more cost effective, and therefore more accessible product, against the environmental impact of using oil-based plastics in manufacturing. A MECO Matrix was created to visualise the kettle's lifecycle from raw material to disposal (Figure 73).

	Materials	Manufacture	Transport	Use	Disposal
Materials	Polypropylene and Stainless Steel for springs.	Oil usage and consumption in Polypropylene production.	Transport from manufacturing facilities will incur further fuel consumption.		Polypropylene malleability allows it to be recycled. As outlined in 'Ktembo Business Case' the materials will upcycled for future products.
Energy	18 MJ required for the entire sub-assembly. [43]	0.21 kWh of energy for the full assembly to be injection moulded. (5250 Joules). [44]	Though there are injection moulding facilities in Kenya at this stage it is difficult to assess whether they have the required capabilities.		Though there is power consumption in the recycling process, there is a net deficit in consumption as recycling offsets the 18 MJ required to source new raw material.
Chemicals	$(C_3H_6)_n$	Ziegler-Natta or metallocene			As above.

	catalyst is used in production.
Other Issues	Once the material has reached its recycling limit it will have to be disposed of and polypropylene's slow degradation can produce toxins such as lead and cadmium.

Figure 73 – MECO Matrix to assess the sub-assembly's lifecycle

3.7.1 Reliability

From use to disposal the polypropylene parts should last longer than all other components (10,000 cycles) and not cause any reliability issues. There is also a small risk of oxidisation of the springs if the stainless steel degrades over time. The main risk to reliability would be the hinge and latch mechanisms' components coming loose, however this risk should be minimal as the parts have been constrained.

All parts can be easily replaced and repaired should any issues occur during the product's lifecycle.

3.8 Drawings/Further Instructions for manufacturers

The tolerances on all plastic injection moulded part drawings are for interfacing components such as holes and rivets, lids, etc. They have been toleranced such that the lower limit of each female part is still larger than the upper limit of its corresponding male part. STEP/STL files will be provided to injection moulding specialists for all other dimensions to be toleranced at ±0.375 mm.

3.9 Limitations

The spout pouring test was conducted with an approximated cardboard model which does not behave in the same way as polypropylene with regards to adhesion.

The advantage of having the valve fixed to the lid was that the user could view the water line as the kettle was being filled. However, upon further observation the spout funnel would not allow sufficient visibility, so a Perspex viewing glass was installed in the bottom of the top casing negating the benefit of the valve being in the lid and the spout being changed to an untested model.

Though the reliability and risks were considered it may have been beneficial to conduct a DFMEA including possible misuse of the product and study the effects of repetitive motion of the lid opening and closing on reliability, along with testing a 3D printed prototype for potential failure modes and weaknesses.

It should also be noted that this sub-assembly design uses all unique parts with no standardisation. Though there are three rivets used in the hinge mechanism that could potentially be standardised with small changes to the design (Figure 74).

Figure 74 – Three separate rivets all with varying lengths

3.10 Conclusion

The aims and objectives of this section were mostly satisfied. The customer was kept at the forefront of the design when considering ergonomics and user behaviour and parts were improved for manufacture, however further improvements could have been made.

The design specification from Table 13 was mostly adhered to, the results of which are documented in Table 17.

Category	Requirement	Achieved Result	Met
Volume	Maximise without compromising ergonomics.	0.75 L, half of the boiling chamber.	Yes
Ergonomics	To be as comfortable and accessible as possible within reason.	Button positioned just above handle allowing one-handed use.	Yes
Efficiency	Minimise heat loss from the lower boiling half.	Ball valve installed but no further insulation from the filter was not installed.	Yes
Safety	Make suitable provisions to reduce any possible risk.	Safety risks were briefly considered, but a more comprehensive risk assessment should be carried out prior to launch.	Partially

User Error	Reduce the possibility of user error.	This would require user testing after product release. However, user error was mitigated as much as possible in the design.	Yes
Cost	Minimise.	Material cost is approximately £0.70 with mould cost totalling £29,000. However, with so many factors influencing cost further business development is required to ascertain an accurate cost.	Yes

Table 17 – Design specification results

4 Casing, Base and Power Cable

4.1 Summary

A product design specification was created for the casing, base, and power cable and from this the core technical challenges identified. The casing needed to be insulative, safe to touch externally and safe to drink from. Stainless steel 304 was therefore selected to be used since it is food safe, and a steady state thermal model was created in Fusion 360 revealing a maximum average surface temperature of 20.2°C. By measuring the temperature against time of a pre-existing vacuum insulated kettle, an estimate of 3.9 hours was calculated for how long our kettle will keep the water hotter than 60°C. A power connection type was selected to provide the sufficient 300W and switches were selected ensuring an easy-to-use operation of the kettle. The process of manufacturing was considered, allowing cost estimations for the three subassemblies to be calculated. It was estimated that the material cost per unit would be £2.62 and £125,990 for all the machinery required. The three subassemblies were then modelled in CAD where future work was identified to redesign the base to be easier to manufacture.

4.2 Overview

The three subsystems that are outlined in this section of the report are the casing, base, and power cable of the kettle. The major design challenges for the casing are designing it to be insulative, safe to drink from and safe to touch at all times of the kettle's operation, ensuring the safety of the user. The base is required to house all the electronics of the kettle. Therefore, the base must be designed to protect the electronics through mountings and ensuring there is a waterproof seal between the base and the casing. The base also houses all the switches that the kettle will be operated by. It is important a switch configuration is designed that will be centred around ease of use for the user. In addition, a power cable assembly needs to be designed that will provide sufficient power to the kettle, to achieve our target boil time of 30.45 minutes for 1.5 litres of water to get to 100°C. This was calculated from the Simulink model in section 1.3.3 of this report.

The cost of the final design is also an important factor since the kettle needs to return a profit. To ensure a good net profit margin of 20%, with the kettle estimated to be sold at £20, the 7 subassemblies must have a combined cost of £16. Therefore, the three subassemblies in this report must cost less than £6.50.

4.3 Design Specification

In order to identify key targets for the three subassemblies a product design specification was devised. The challenges regarding the interfaces between subassemblies were also considered, since the kettle should be designed with an overview of how the systems will be integrated.

4.3.1 Product Design Specification

Table 18 - Product Design Specification

	Category	Requirement	Target	Must/ Wish	Method of Evaluation
Combined Subsystems	Feature	Cost	Combined cost of casing, base, and power connector subassemblies less than £6.50	Wish	Cost estimation
Interfaces	Durability	Water Resistance	Waterproof join between the casing body and base to protect the electronics	Must	CAD design
	Performance	Secure connection	Casing body must be securely connected to the base	Must	CAD design
	Performance	Secure connection	Handle securely connected to the base	Must	CAD design
	Performance	Secure connection	Top casing securely connected to the base	Must	CAD design
Casing	Performance	Safe Temperature	External casing body safe to touch at all times ≤44°C	Must	Thermal Model
	Performance	Thermal Insulation	Casing body is efficient at insulating – above 60°C for 3 hours	Must	Prototype
	Feature	Food grade	Food grade casing so water is safe to drink	Must	CAD design
	Performance	Easily fillable	Easy to identify when water level is maximum	Wish	CAD design
	Feature	Manufacturable	Easy to manufacture	Wish	CAD design
Base	Feature	Stability	Keep kettle stable - centre of mass of the kettle passing through base	Must	CAD design
	Feature	Size	House all electronics and switches securely	Must	CAD design
	Durability	Electronics	Electronics protected from heat of the kettle	Must	Thermal Model
	Durability	Electronics	All electronics securely mounted	Wish	CAD design
	Feature	Switch operation	Easily operated switches	Wish	Technical specification of selected switches
	Feature	Manufacturable	Easy to manufacture	Wish	CAD design
Power Connection	Performance	Power	Provide 300W of power	Must	Technical specification of selected power connection
	Feature	Usability	Easy to connect to socket	Wish	CAD design

	Feature	Suitability	Suitable for most solar home systems	Wish	Technical specification of selected power connection
	Feature	Manufacturable	Easy to manufacture	Wish	CAD design

4.3.2 Core Technical Challenges

The core technical challenges were identified from the "Must" specification points of the PDS. These core technical challenges were then prioritised through consideration of the consequences that would occur if the points were not met.

Table 19 - Priority ranking of core technical issues

Specification Point	**Consequence if not achieved**	**Priority ranking (1 is highest)**
Finding a power connector that provides enough power.	Kettle will not boil water as efficiently	3
Casing body is safe to touch externally, efficiently insulative and safe to drink from.	User may burn themselves if casing is too hot and dangerous to drink water from a non-food grade material	1
All connections between subassemblies are secure.	Kettle may disassemble if connections are not strong enough	4
Electronics mounted so they are unable to come in contact with water and protected from the heat of the kettle.	Kettle will stop working if electronics become damaged	2

The technical challenge with the highest priority is the design of the casing body. It must be efficiently insulative, allowing the water to retain its heat after boiling. This will reduce the number of times the kettle needs to be boiled, saving the user time, energy and as a result cost. The stainless steel used must also be safe to drink from so the health of the user is not compromised by using the kettle. Furthermore, it must be safe to touch externally (at a low temperature) so the user does not burn themselves.

The second technical challenge to prioritise is the mounting of the electronics in a way that protects them from the heat of the kettle and prevents them getting wet. This is followed by selecting a power connection which will provide the kettle with enough power to boil 1 litre of water in 17 minutes (as outlined in the heating section of the technical feasibility study) [45].

All of these technical challenges need to be solved whilst also aiming to be a low cost, easily manufacturable design, that is easy to operate and compatible for most people with a solar home system.

4.4 Concept Development

The technical feasibility study [45] revealed double wall stainless steel vacuum insulation was 12.2 times more efficient than the next best form of insulation analysed. However, the technical feasibility study assumed that a perfect vacuum was formed. This is not possible outside of theory, due to manufacturing limitations. As a result, analysis needs to be done to determine how long the water will remain hot in the final kettle and to determine the temperature of the casing externally.

4.4.1 Vacuum Efficiency

The manufacturing section of the technical feasibility study suggested that the vacuum in the casing would be created by using a vacuum furnace [45]. The casing will have a glass bead placed over a hole in the casing, so when the vacuum furnace evacuates the air, the glass bead will melt, sealing the hole in the casing. This results in a vacuum layer being formed between the two layers of stainless steel.

Research into vacuum furnaces that are currently used to create vacuum insulated flasks, revealed an operating vacuum pressure of 5000Pa. Using 100,000Pa as atmospheric pressure, a vacuum furnace will evacuate 95% of air and as a result, the vacuum in the final casing design was assumed to have 95% of air evacuated [46].

4.4.2 Pre-existing Product Analysis

It was assumed that pre-existing vacuum insulated products have the same level of air evacuated. In order to prototype how long the vacuum insulation would keep the water in our kettle hot, a digital thermometer with a thermocouple was attached to the inside of the "Kinox" kettle, a pre-existing AC powered vacuum insulated kettle [47]. The kettle was filled with 1 litre of water and boiled. The temperature was then recorded at regular 20-minute intervals and the results are presented in Figure 75.

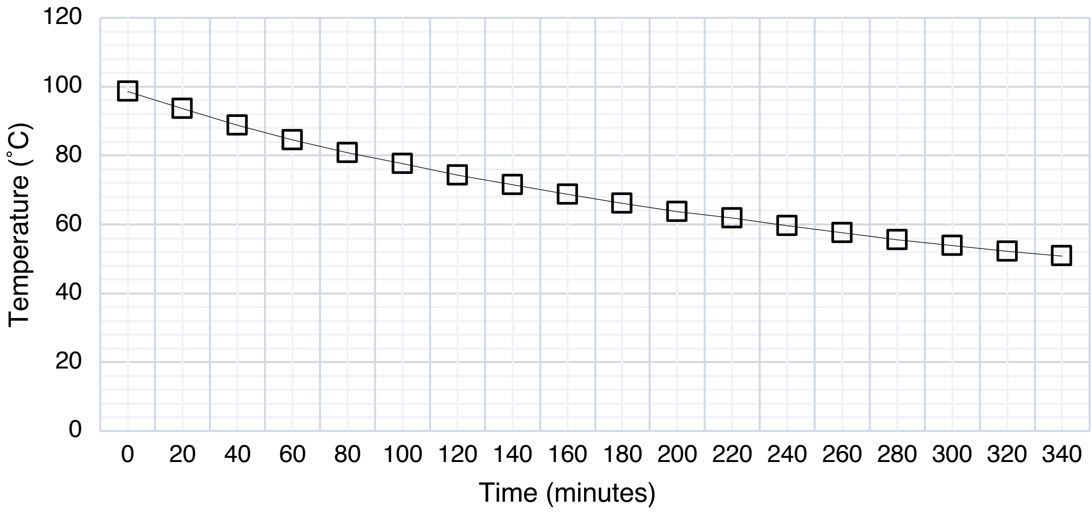


Figure 75 - Temperature against time graph for "Kinox" kettle after boiling

With the assumption that our kettle would have a thermal efficiency greater than or equal to the "Kinox" kettle, it can be estimated our kettle will keep water hotter than 80 degrees for 85 minutes and above 60 degrees for 3.9 hours.

4.4.3 Stainless Steel Selection

In order to determine which grade of stainless steel would be most suitable for use in the final casing design, properties were assessed for the 5 families of stainless steel (austenitic, ferritic, martensitic, duplex and precipitation hardening). Selecting a grade of stainless steel that is easily welded and ductile will make manufacturing easier. A high temperature resistance and good corrosion resistance will ensure the steel is durable enough for use in the kettle, where it will be subjected to water boiling temperatures.

Table 20 - Stainless steel family properties, adapted from [48]

Family	Weldability	Ductility	Temperature resistance	Corrosion resistance	Common Grades
Austenitic	High	High	High	High	304, 316
Ferritic	Low	Medium	High	High	430
Martensitic	Low	Low	Low	Medium	410, 420
Duplex	High	Medium	Low	Low	2205
Precipitation Hardening	Low	Medium	Low	High	630

Table 20 revealed that an austenitic stainless steel would be most suitable, as it outperformed all the other families with reference to the properties analysed. The two most common grades within this family are 304 (composed of 18% chromium and 8% nickel) and 316 which has less chromium and increased levels of nickel and molybdenum in its composition. Due to its composition 316 has a better resistance to corrosion however it is more expensive. It is mostly used for medical grade applications, whereas 304 is cheaper but still considered a food safe grade.

There are no specific UK regulations for stainless steel uses in the food industry. However, the European Framework Regulation (EC) No. 1935/2004 provides an overview of the general safety requirements a material must have to be safe when in contact with food, all of which the 304-grade stainless steel meet [49]. Therefore, the kettle casing body will be made from sheets of stainless-steel 304, as it is easily weldable, machinable and safe to drink water from.

4.4.4 Thermal Model

In order to analyse the external temperature of the casing, a CAD model was created for this subassembly. This was used to create a steady state thermal simulation within Fusion 360. A temperature of 100˚C was applied to the 1.5 litres of water within the casing. This is the hottest temperature the water will be since the kettle will switch off once boiling is achieved. Therefore, if it is safe for the user to touch the external casing at this temperature without burning themselves, it is assumed safe to touch at any time, and the highest priority specification point of the PDS will have been achieved.

An ambient temperature of 20˚C was used in the thermal simulation. Convection thermal loads were modelled between the water and inner casing, the inner casing and vacuum, and the vacuum and outer casing. An average heat transfer coefficient ($\bar{h}$) of 340W/m^{2}K was used from the water to the stainless-steel. The average heat transfer coefficient from steel to air is 7.9W/m^{2}K. Since the vacuum layer is assumed to have 95% of air evacuated, an average heat transfer coefficient for the vacuum layer was assumed to be 0.395W/m^{2}K which is 5% of 7.9W/m^{2}K. The same value was used for the vacuum to steel average heat transfer coefficient [50]. Finally, an emissivity of 0.075 was used for the stainless steel and the results of the model can be seen in Figure 76 [51].

The model was then rerun with altered values of $\bar{h}$ to model the casing where air is present between the two casing layers and not a vacuum, seen in Figure 77.

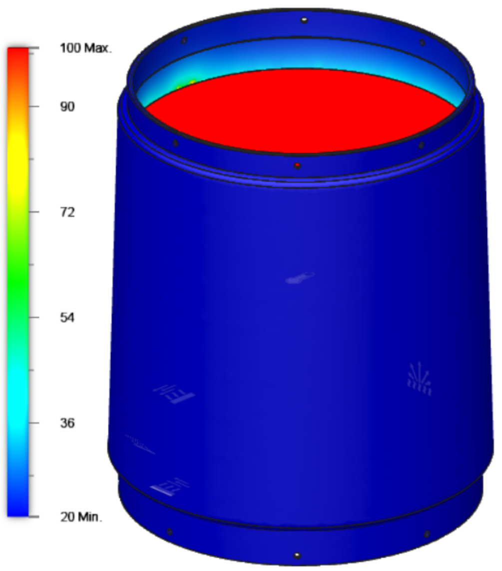


Figure 76 - Thermal model of double wall stainless steel vacuum casing, modelled with water at 100˚C

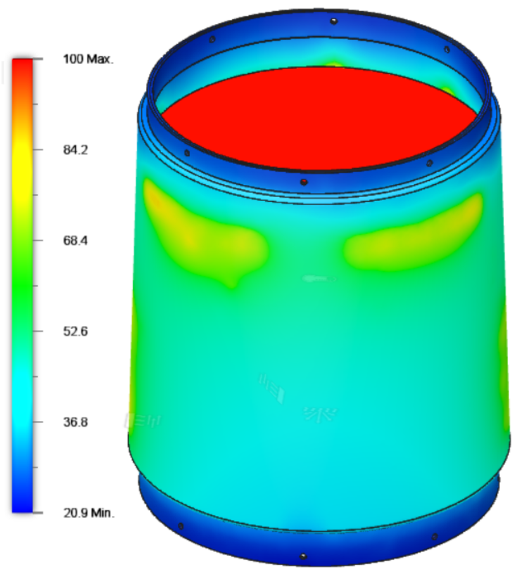


Figure 77 - Thermal model of double wall stainless steel casing without a vacuum layer, modelled with water at 100˚C

The average surface temperature of the casing with a vacuum was calculated to be 20.2˚C. At this temperature, the kettle will be safe to touch externally since the health and social care sector of the UK Government state temperatures must not exceed 44°C for risk of burning [52].

When the casing is modelled with air between the inner and outer layers, the external temperature is much hotter at around 50˚C, as seen in Figure 77, highlighting the efficiency of vacuum insulation. Hotter regions can be seen nearer the top of the casing in Figure 77, and this is assumed to be because of how the layers have been designed where they are closer together at the top compared to the bottom. Using the model as an estimation for the worst-case scenario, there is confidence that the casing with a vacuum will be safe to touch at any time during or after the in the kettle has boiled.

4.4.5 Electronics Protection

As concluded in the heating section of the technical feasibility study, a nichrome heating element will be used in the final design. These elements are welded to a heating plate, located in the bottom of the kettle, and work by heating this plate up. The heating plate will separate the base subassembly from the inside of the casing subassembly. It was therefore important that this boundary is waterproof to prevent the electronics getting wet. This was achieved by designing the inner casing wall so the plate could be MIG welded around its circumference to the inner casing wall, to provide a waterproof interface between the base and casing subassemblies. By achieving this the electronics mounted in the base will be protected against water exposure, fulfilling an important specification point of the PDS.

4.4.6 Power Connection

The Simulink model and electronic circuit is designed to operate with 300W at 12V DC power.

$$P = VI$$

Equation 1

By rearranging Equation 1 it was calculated 29A or more of current is required to power the kettle efficiently. A plug and socket that matched this criterion was located using RS components, an electrical products supplier Figure 78 and Figure 79 show the selected components. Since they are designed for use with 40A and 500V, they will be able to provide sufficient power with a 12V supply [53] [54].

Figure 78 - Selected power socket

Figure 79 - Selected power plug

The plug needs to have a fitting on the other end which will allow it to be used by most people with a solar home system. Research into solar home systems revealed that there is no universally used plug connection type. A conversation with M-KOPA, a solar home system company based in Kenya, revealed that these connections are custom made (see Appendix C). Many people in Kenya use their solar home systems to charge a car battery. Therefore, it was decided that the power cable subassembly should have heavy duty crocodile clips which would attach to the terminals of the user's battery. The user would also be supplied with a spare power connector plug. This could be used to create a power cable subassembly of the user's own, operating with their solar home system connection input. Whilst this means the user can not immediately plug the kettle into their solar home system, it is the best possible solution as the crocodile clips will allow most customers to find a way to power their kettle.

4.4.7 Design Development

In order to accommodate the changing design of other subsystems an iterative process was adopted. This was prevalent in the design of the fill line which informs the user when the kettle water level is at a maximum. Initially the casing was designed to have embossed text with a line, seen in Figure 80.

Figure 80 - Initial design of the maximum fill line

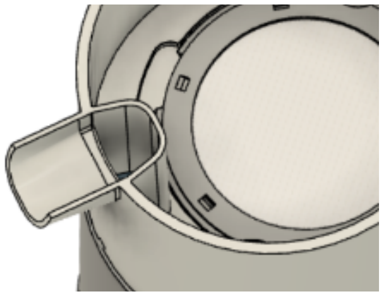


Figure 81 - View of fill line not possible due to smaller spout than anticipated

This would be viewed through the spout when the lid was opened. However, complications with the spout design in integrating the steam release mechanism into the lid, resulted in a smaller spout than anticipated (Figure 81), making it very difficult to see the fill line. The fill line was therefore modified to span half the circumference of the casing, seen in Figure 82, and a transparent PMMA plastic fill window added to the top casing, allowing the fill line to be much more visible (seen in Figure 83).

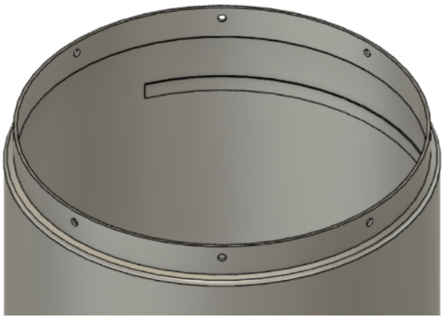


Figure 82 - Adapted fill line design of the inner casing

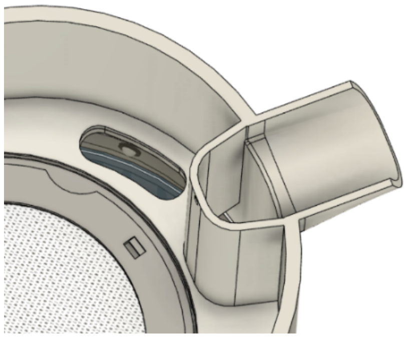


Figure 83 - Addition of the fill window to allow user to see the maximum fill line

4.5 Design Embodiment

4.5.1 Switches

The base subassembly needs to accommodate the switches that will operate the kettle. For simplicity it was decided to mount the switches in the base, rather than elsewhere on the kettle. This was to minimise the distance of the wiring between the PCB and switches.

Initially, it was thought that there would be a single switch which would be operated with a twist motion to select one of the dual mode temperatures, followed by a push motion to turn it on. However, it was decided that this may be an over complicated solution, requiring a specialised type of switch. For ease of use by the customer, and for ease of manufacturing and design, it was decided that two switches would be used. One to control the temperature and the other to turn the kettle on.

Figure 84 - Momentary push LED button used to turn the kettle on [55]

Figure 85 - Rocker switch used to select one of the dual mode temperatures [56]

It was decided a single pole double throw, momentary LED push button switch would be used to turn the kettle on (Figure 84). The LED light will inform the user the kettle has been turned on. For the temperature selection switch a single pole double throw on-off-on rocker switch was selected (Figure 85). The button would be customised to have the temperatures on the face of the button, so the user can clearly identify the dual mode temperature they have selected.

4.5.2 Base

Injection moulding allows for a fast production rate and produces parts cheaply once the high setup costs of moulds have been paid for. Therefore, the base and base bottom will be injection moulded polypropylene. Due to the high complexity of the part designed, the moulds that will need to be produced will be expensive at an estimated cost of £20,000 [57]. The base will need to be CNC machined after it is moulded to produce holes. These will be required for the switches to be housed in and for the electrical wiring to go through. Holes will also be needed for bolts. 7 M3 bolts attach the casing to the base and 2 M5 bolts attach the handle to the base. The holes for the handle will need to be threaded with a thread tap. The PCB will be mounted to the base bottom using L shaped plastic brackets and the socket will be housed inside a bracket.

The base subassembly may need to be iterated in order to make it easier to manufacture potentially by designing the base to be in two parts that are joined together. This is because it may not be possible to remove the current design from an injection mould due to draft angles. Furthermore, sections of the base are thick and injection moulding is usually to create thicknesses less than 4mm [58]. Due to limitations in time, it was not possible to redesign this part, but future work should be focused on this.

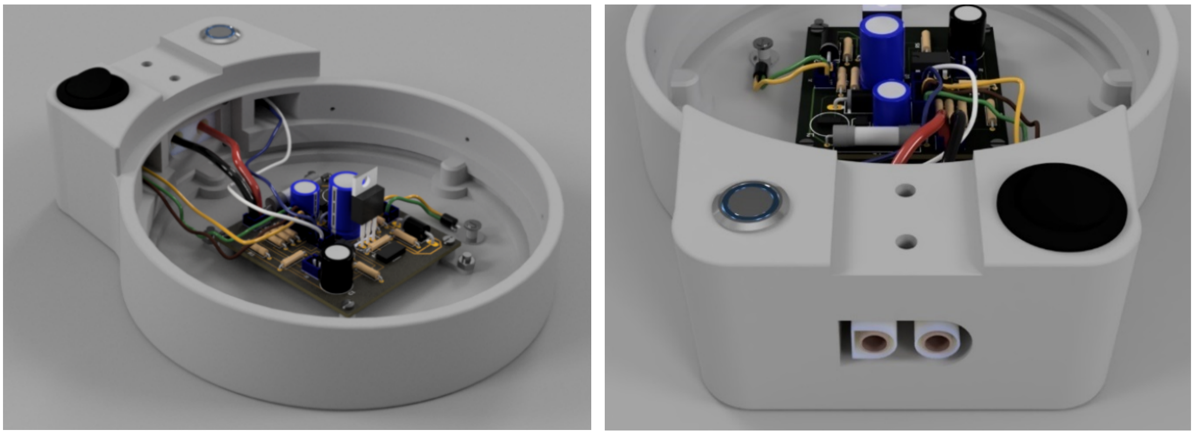


Figure 86 - CAD renderings of the base subassembly

4.5.3 Casing

The inner and outer casing will be made from stainless steel 304 sheets that are CNC machined to have holes in appropriate places. The holes that would need to be drilled to form the inner or outer casing can be seen in Figure 92. In order to maximise the number of kettles that can be made at once, the design will be repeated many times across a large steel sheet (Figure 88).

Figure 87 - Example single sheet layout of one casing

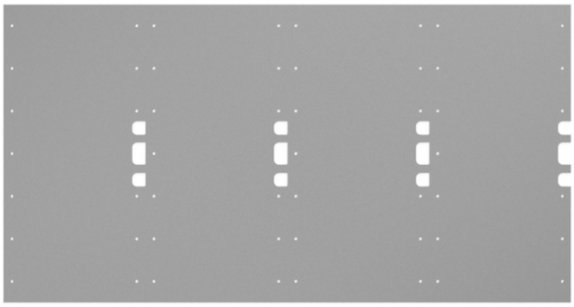


Figure 88 - Example layout of the CNC machining to be performed on stainless steel sheets

The large sheet will then be placed in a pipe former welder machine to form a cylindrical shape. This will then be split into individual parts with a pipe cutting machine. The cylinders will then be placed in a hydroforming machine which uses water to expand the cylinder to the desired shape in a mould. For example, the change in geometry that would occur for the inner casing can be seen from Figure 89 to Figure 90.

Figure 89 – Inner casing cylinder formed from the pipe former and welder

Figure 90 - Cylinder after it has been hydroformed to desired geometry

The inner and outer casings are then assembled and welded around their circumference. This is then placed in a vacuum furnace with a glass bead on the hole in the inner casing seen in Figure 91. The air is then evacuated in the vacuum furnace and the temperature increased until the glass bead melts, sealing the vacuum layer. The design for this can be seen in the casing subassembly technical drawing, section view B. The vacuum can then be tested by heating the inside of the casing and seeing if the outside gets hot. If it does heat up, then the vacuum process has failed and the vacuum process needs to be repeated.

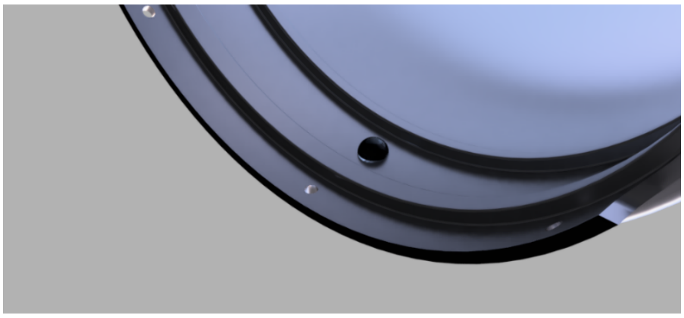


Figure 91 - CAD render of the glass bead over the hole in the casing assembly, before it is melted in the vacuum furnace

The stainless steel 304 heating bottom plate is then formed from a deep drawing machine and scrap material is cutaway. The heating element is welded to the heating bottom plate which is then welded to the casing. This weld must be checked since it is critical it is watertight to meet the specification point in the PDS of protecting the electronics from water. The quality control team will randomly test a certain number of these components by filling them with water and checking there are no leaks. Finally, the 7 M3 bolts will connect the casing subassembly with the base.

4.5.4 Interfaces

As outlined in the product design specification, all connections between the subassemblies must be secure. Hence, work was done collaboratively with the top casing team to ensure an effective interface was designed. Holes have been placed at the top of the stainless-steel casing to allow plastic rivets to connect the top casing subassembly to the casing subassembly. A gasket (seen in Figure 92) was designed to sit in this join, providing a seal to prevent water leaking.

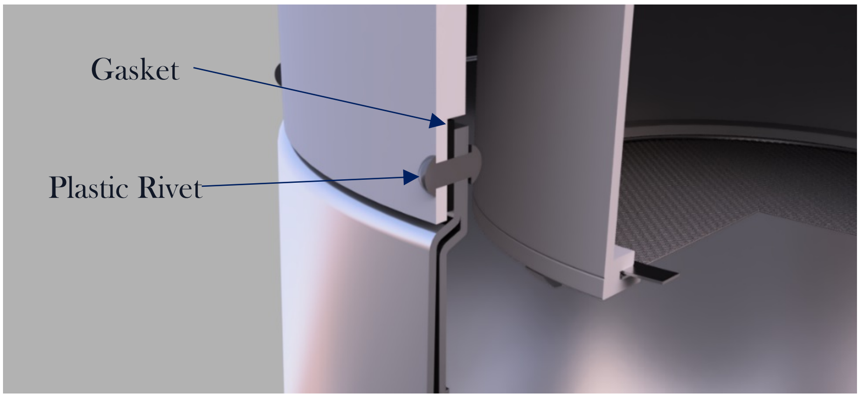


Figure 92 - CAD render of the gasket used to seal the join between the top casing and casing subassemblies

4.5.5 Manufacturing Overview

A summary of the manufacturing and assembly processes, required to make the casing and base subassemblies, can be seen in Figure 93.

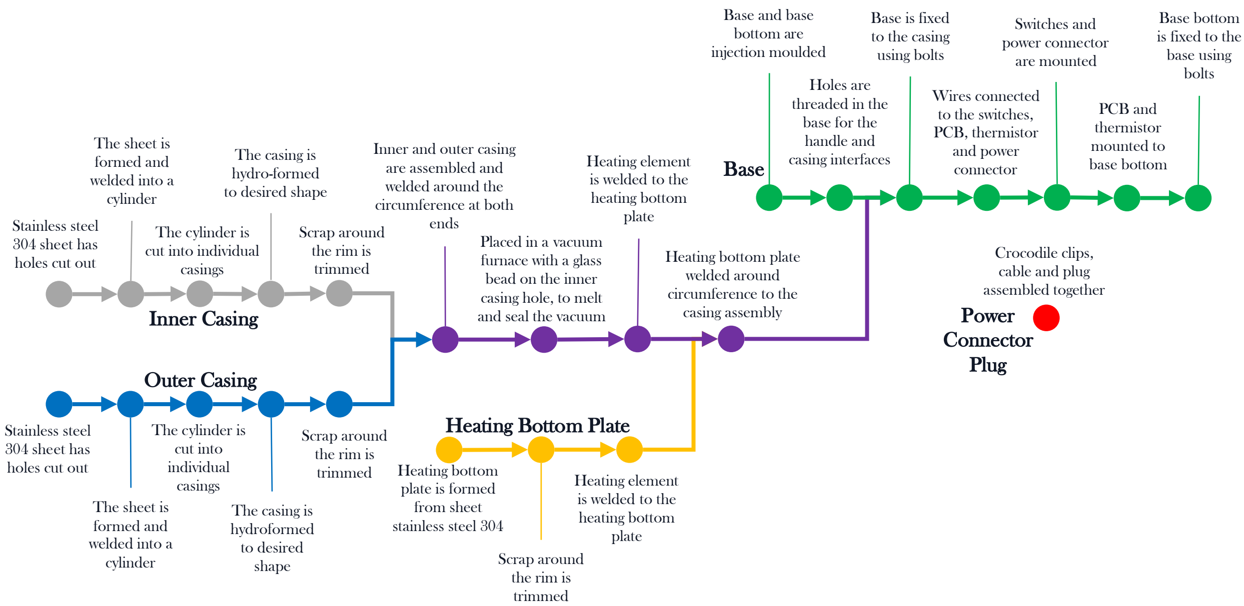


Figure 93 – Stages of manufacturing and assembly

4.5.6 Material Cost Estimation

An estimation of the cost per kettle for the casing and base subassemblies was calculated. It was assumed that the product would be made in a large quantity, hence bulk trade prices were used. A cost of £2.50/kg was assumed for the polypropylene pellets that would be used in the injection moulding [59]. The base and base bottom, have a mass of 181g and 61g respectively and hence would cost £0.72 in materials. The remaining components were then cost estimated, seen in Table 21.

Table 21 - Cost estimation of parts

Subsystem	Component	Part No.	Material	Quantity	Cost	Total Cost	Source
Base	Electrical Wire	UOBG6_PART_0024	Electrical Wire		£0.042/m	£0.04	[60]
Base	Momentary on switch	UOBG6_PART_0014		1	£0.28	£0.28	[61]
Base	Rocker switch	UOBG6_PART_0013		1	£0.07	£0.07	[62]
Base	Nuts, Bolts and Plastic rivets	UOBG6_PART_0019	Steel and plastic	24	£0.01	£0.24	[63]
		UOBG6_PART_0018					
		UOBG6_PART_0021					[64]
		UOBG6_PART_0022					
		UOBG6_PART_0020					
		UOBG6_PART_0023					[65]
		UOBG6_PART_0025					
Base	PCB Mounting feet	UOBG6_PART_0015	Plastic	4	£0.01	£0.04	[66]
Power cable	Plug	UOBG6_PART_0075		2	£0.495	£0.99	[53] [54]
Power cable	Cable	UOBG6_PART_0075		1	£0.042/m	£0.04	[67]
Power cable	Crocodile Clips	UOBG6_PART_0073		2	£0.10	£0.20	[68]

The plug and socket selected for the kettle are specialist power connections made by RS components (a company which does not normally sell in large quantities for manufacturing) therefore finding a bulk trade price was not possible to locate [53] [54]. It was assumed an equivalent power connection from a different supplier would be sourced where they could be bought in bulk. A 50% reduction of the individual price RS components charge was therefore assumed, due to the large quantity of components that would be purchased. Hence the plug and socket was assumed to have a combined cost of £0.99.

Therefore, the material and component cost of the base and casing subassemblies (excluding the cost of the PCB and thermistor) is estimated at £2.62. However, this does not account for the cost of the machinery required to manufacture the kettle, hence Table 22 was created.

4.5.7 Machine Cost Estimation

The cost of the injection moulding machine was not considered as only the moulds will need to be purchased. This is because these parts will be made by a supplier and shipped to Kenya for assembly.

Table 22 - Cost estimation of machinery required for the manufacturing of the base and casing subassemblies

Machine		Use	Cost	Source
CNC pillar drilling machine		• To drill holes in the stainless-steel sheets. The holes are used to join the casing to the top casing and base, and to pass wires through to the switches.	£4750	[69]
Pipe former and welder		• To turn the steel sheets into cylindrical shape	£8500	[70]
Pipe cutter		• To separate the cylinders into individual parts	£700	[71]
Hydroforming machine		• To form the geometry of the inner and outer casing from the stainless-steel cylinders	£12,750	[72]
Deep drawing Machine		• To form the heating bottom plate	£7090	[73]
Scrap cutting machine		• Trim scrap from the hydroformed cylinders • Trim scrap from the deep drawn heating bottom plate	£5000	[74]

Automated circumference welder		• Weld the top and bottom circumferences of the inner and outer casing together • Weld the heating element to the bottom heating plate • Weld the bottom heating plate to the casing	£700	[75]
Vacuum furnace		• To form the vacuum layer between the inner and outer layers, achieved by evacuating the air and melting a glass bead to seal the cavity in the inner casing	£86,500	[76]
Injection Moulds		• To create the base and base bottom	£20,000 due to complexity	[77]

4.6 Conclusion

The key core technical challenges were identified from the PDS. This included designing a casing body that is safe to touch externally, efficiently insulative and safe to drink from. This was achieved through thermal modelling and analysis of pre-existing vacuum insulated products. The Fusion steady state thermal model estimated an average maximum surface temperature of the eternal casing of 20.5°C. The stainless steel 304 is a suitable material to make the casing out of since it is safe to drink from and easily machinable.

Another technical challenge known was mounting all of the electronics in the base and ensuring they would not get wet. This will be done by welding the heating bottom plate to the casing and using quality control to ensure the weld is waterproof. The other core technical challenges were solved by sourcing a power cable which would provide 300W to the kettle from RS components and designing all of the connections between subassemblies to use bolts or rivets with rubber seals where necessary, to ensure secure interfaces.

Other points achieved from the product design specification were making it easy to identify when the water level is maximum, via a fill window in the top casing, and designing the base to house all the switches. The use of crocodile clips in the power cable assembly makes the kettle usable by most people with a solar home system and the casing and power cable assembly were designed to be easily manufacturable. Future work has been identified in redesigning the base as it may not be possible to injection mould the current design due to draft angles. The base should be redesigned to be formed in two parts that are connected together. Finally, the combined cost target of producing the casing, base, and power connector subassemblies for less than £6.50 was achieved, with a total cost estimation of £2.62.

5 Heating Element and Electronics

5.1 Summary

In developing countries, access to a national grid is uncommon, resulting in the need for solar home systems and mini grids that supply individual households or small communities. Both provide DC electricity that is stored in a 12V lithium-ion battery. The task was to produce a kettle that can boil water using the small amount of power available without inconveniencing the user.

The heat generated by the resistive heating element increases with the current, therefore, designing a circuit that could increase the current supply to the heater would increase the rate of heating. It was decided that a Darlington pair transistor would be used to action this, providing a balance between improved performance, and maintaining low costs. The PCB manufacture would occur in China to utilise the expertise and piece price of the companies there, it was deemed to negate the extra transport costs incurred. Assembly of the PCB into the kettle would take place in Kenya, with any repairs and a final quality assurance check also. Only components that meet the RoHS regulations have been selected to avoid polluting the environment, with lead-free also being used on the PCB. Whilst there has been a focus on cost reduction, in some areas quality took priority, leading to a higher cost that was initially estimated once transportation has been accounted for.

5.2 Introduction

5.2.1 Problem Identification

The aim of this project is to create a super-efficient kettle, meaning a large focus is placed on energy transfer. The heating sub-system transfers the electrical energy provided by a solar home system or mini grid into thermal energy to heat the water. As well as boiling water, a key objective of the kettle is to provide the user with clean water.

Prior research conducted for the TFS showed that there was a 6% increase in efficiency when heating water to 70°C compared to 100°C [4]. It was concluded in this study that a dual-mode kettle would be a good solution, providing both clean, safe drinking water, and the improved efficiency of lower temperature heating. This report details the background, design decisions, and predicted performance of aspects of the proposed solution.

5.2.2 Technical Challenges

Given the kettle was designed for off-grid Kenya it must be DC powered, ergo, the boiling times are going to be longer than for an equivalent volume of water in a 2kW AC kettle. Typical solar home systems supply power through lead-acid batteries that can provide 150W at 12V, but outputs can vary from 50W to 350W [78] [79].

Figure 94 shows the boiling time for different input powers. As expected, the time to reach 100°C increases as the input power decreases. This demonstrates the key challenge of using DC sources to boil a kettle, and the importance of creating a circuit that can maximise the power available.

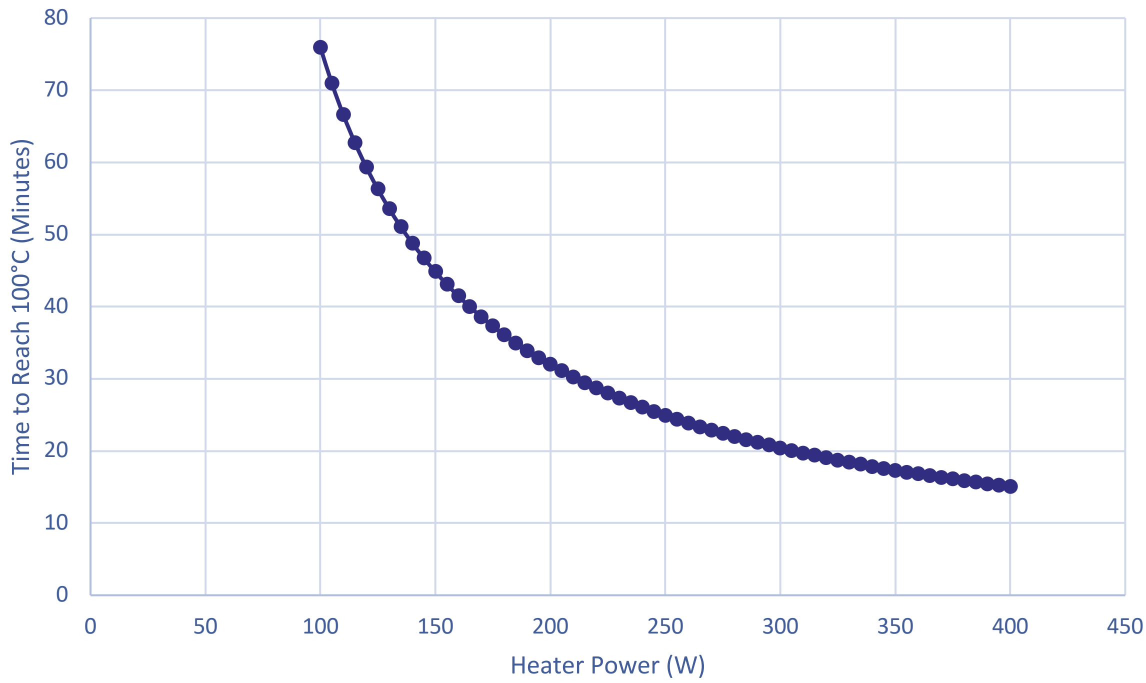


Figure 94 - Time to reach 100C for different input powers.

With unlimited budget and space, it would be possible to compete with the boil times of an AC kettle, however, the product is a household appliance for those in less developed regions. The kettle cost and ergonomics are very important metrics that determine the success of the design. As a consume product, especially one for sale in countries with low average incomes, the compromise between cost and functionality is forefront.

5.3 Design Specification

Alongside the general specification points for the product, specific electronics related criteria were set due to the importance of the subsystem. The significance of each of the requirements was realised by defining whether it was a must or a wish.

Table 23 - Circuit Design Specification

Requirement	Target	Must/Wish	Method of Evaluation
Power Source	Powered by 12V DC	Must	Simulation and prototyping
Lifespan	Have a lifetime of 10,000 boil cycles	Must	Product testing
Boil Time	Boil time for 1L of water should be under 20 minutes	Wish	Simulink model and calculations
Water Quality	Improve quality of water through water temperature exceeding 65°C for 1 minute	Must	Calculations and prototyping
Cost	Heater and electronics cost within £10	Must	Cost of materials and manufacture
Size	Compact PCB that fits in kettle base	Must	CAD check
Strength	Components and connections are robust	Must	Product Testing
Maintenance	Easy access to key components for repair	Wish	CAD check and prototyping

5.4 Design Solution

5.4.1 Product Design

The World Health Organisation states that heating water at 65°C for 60 seconds results in a 99.999% reduction in active pathogens. [80] To reduce the coding complexity, and incorporate a safety factor, the final water temperature after which the water has been heated past 65°C for 60 seconds needs to be calculated. Figure 95 below shows the boiling curve for a heater power of 150W, the average available power, which will provide the worst-case scenario. The water reaches 65°C at approximately 34 minutes from the start and will be 68°C 1 minute after.

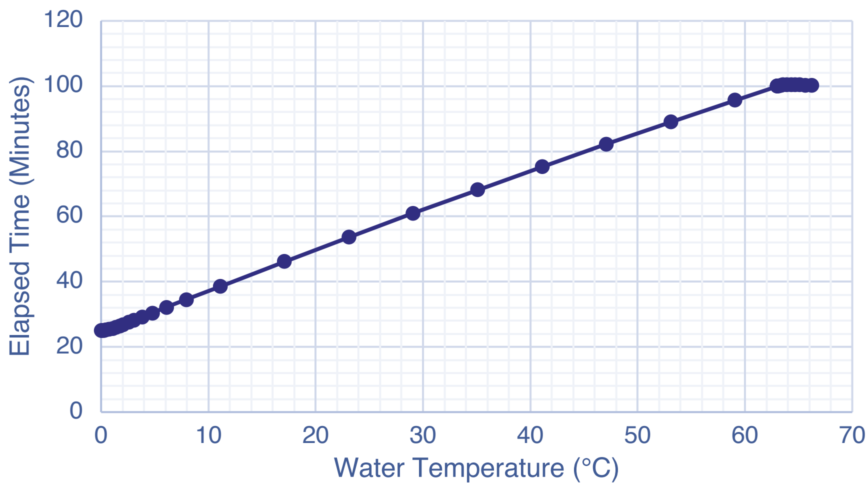
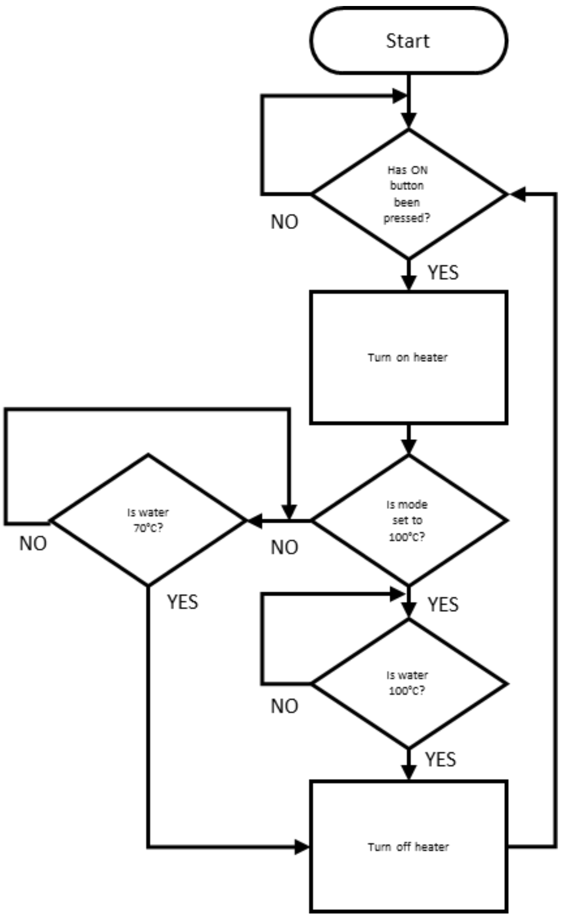


Figure 95 - Boiling curve for an input power of 150W.

Using this information, the sterilise and boil operation modes of the kettle will be calibrated to water temperatures of 70°C and 100°C respectively. A final value of 70°C will be used to provide an additional safety factor to account for any inaccuracies in the electronics.

The flowchart below shows the operating sequence of the kettle, providing a design structure for the circuit and a basis for the code.



5.4.2 Circuit Design

As a result of having a multi-mode kettle, the electronics are more complex than one might find in a typical kettle. The circuit diagram can be seen in Figure 96. The circuit has been separated into the power, decision, amplification, and output functions.

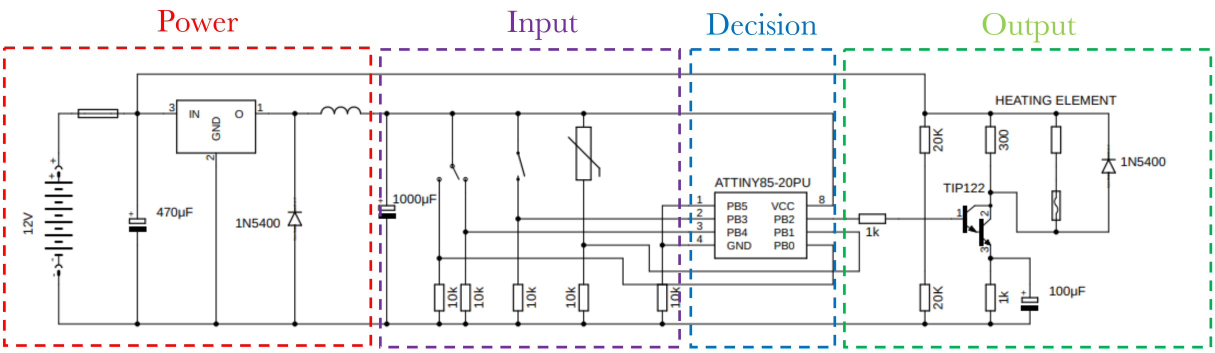


Figure 96 - Kettle Circuit Diagram

5.4.2.1 Power

The circuit is powered by a 12V battery, as it would be when used by the consumer. A fuse has been included in the circuit as overcurrent protection for the electronics. Whereas in a typical household appliance the fuse would be situated in the plug, as the kettle is designed to be used in various environments with multiple power leads, it is impractical and unsafe to place the fuse in the connector. Although having the fuse on the PCB makes it more difficult to replace if it blows, it is an essential safety device. It also provides security in the case of the heating elements short circuiting against the casing.

The voltage regulator provides a potential difference step down to 5V from 12V. The microcontroller and some passive components could not operate with such a high voltage. This is followed by an inductor; this provides a smoother current from the DC power supply through the magnetic field in the inductor. The two capacitors are also there to provide a steadier current.

5.4.2.2 Decision

The first stage of the decision process is the input devices. As described with the operating sequence flowchart, there are two switches: one to turn the kettle on, and one to toggle between the two heating modes. The latter, a Single Pole Double Throw (SPDT) rocker switch is connected to PB0 and PB4, with the momentary power switch connected to PB5. Due to limitations with the electronics software, the momentary switch has been modelled as a Single

Pole Single Throw (SPST) latching switch, however, the connections are identical to those used with a push to make switch.

The temperature control is detected by a negative temperature coefficient (NTC) thermistor. The transducer is connected to PB1, an analogue input pin on the microcontroller. As the temperature increases, the resistance decreases, supplying a differential potential difference. The thermistor is calibrated to determine the component resistance at the threshold water temperatures of 70°C and 100°C, allowing the heating element to be switched off at the correct time.

All three input components are connected to ground through 10kΩ resistors. The pull-down resistor holds the logic signal near to zero volts by pulling the input voltage down to ground to prevent a floating input pin on the microcontroller.

The microcontroller chosen for this system is an Atmel ATTINY85-20PU 8-bit Dual-In-Line package integrated circuit, the datasheet for which can be found in Appendix F. A chip was required that could accommodate four inputs, including one which is analogue, and one output. The ATTINY85-20PU has six general-purpose inputs and outputs, meaning there is one spare pin which has been pulled to ground.

5.4.2.3 Amplification

A resistive heating element relies on a high current supply to produce the maximum heating effect. To increase the current without increasing the supply voltage, an amplifier is required, in this case, a common transistor collector amplifier has been selected. The transistor is a TIP122 NPN Darlington pair. A Darlington pair transistor has been chosen over a standard NPN transistor due to its very high current gain and low input impedance. Another advantage over other forms of gain such as operational amplifiers is the simplicity, only a few components are needed to produce significant current increases. A 1kΩ resistor feeds the base of the transistor as the switching voltage for the transistor is approximately 0.7V. The other resistors form the amplifier, their values dictate the gain achieved.

5.4.2.4 Output

The heating element is represented by a resistor in the circuit schematic. It is connected to the 12V rail and the collector of the TIP122 transistor to achieve the desired current gain. To protect the kettle in the instance of a dry-boil, or an electronics malfunction that prevents the heating element being switched off, a bi-metallic breaker switch has been placed in series with the heater. If the temperature rises above a certain point, the bi-metallic strip will deform, breaking the connection to power. The switch automatically resets once the temperature has dropped, allowing the metal bend back to the neutral position. In parallel with the heating element is a diode to prevent back electromotive force (EMF) leading to high voltage spikes.

5.4.3 PCB Design

Due to the relative complexity of the electronics, a printed circuit board (PCB) was required to house the microcontroller and the passive components. When designing the PCB, the aim was to make the board as compact as possible to ensure it could be housed in the kettle base. Components such as pull-down resistors and the smoothing capacitor and inductor were place in close proximity to reduce the need for long traces. This offered two advantages; it enabled the board to be compact and reduced the PCB cost through fewer operations and lower copper content.

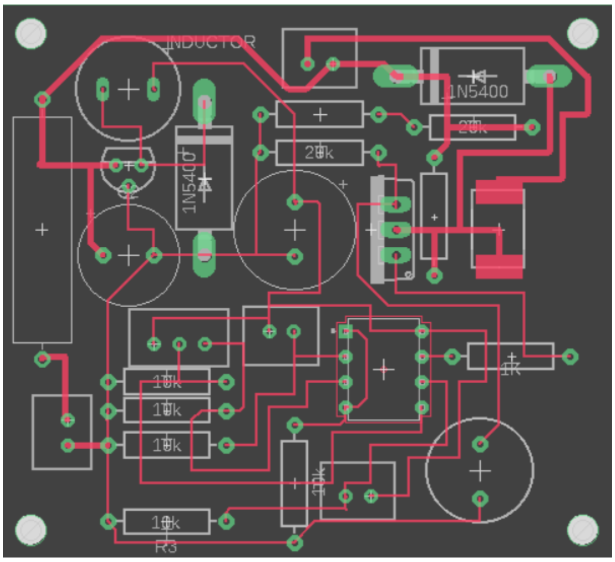


Figure 97 - PCB layout

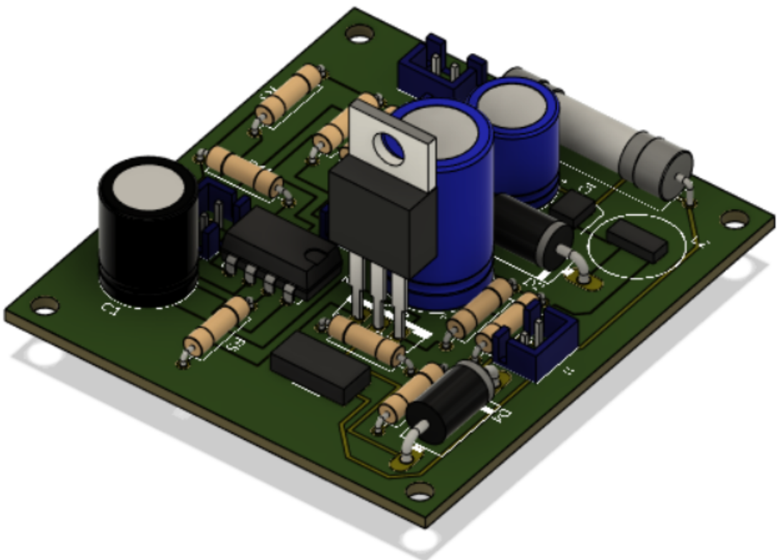


Figure 98 - PCB CAD render

As the key components, such as the heating element and switches, are not board mounted, flying leads are needed to connect them to the PCB. Single-In-Line (SIL) connectors are soldered to the PCB, into which a female connector on the component will be plugged. Using SIL pins rather than soldering the connecting wires directly to the PCB allows for easier assembly and means individual parts can be replaced quickly without the need to remove the board from its mounting or de-solder the component. A disadvantage of using SIL pins is that the physical connection is weaker, with only an interference fit holding the wire in place. To reduce the risk of a wire being pulled out of the board, hooks will be fitted to the vase for the flying leads to pass through, relieving cable strain.

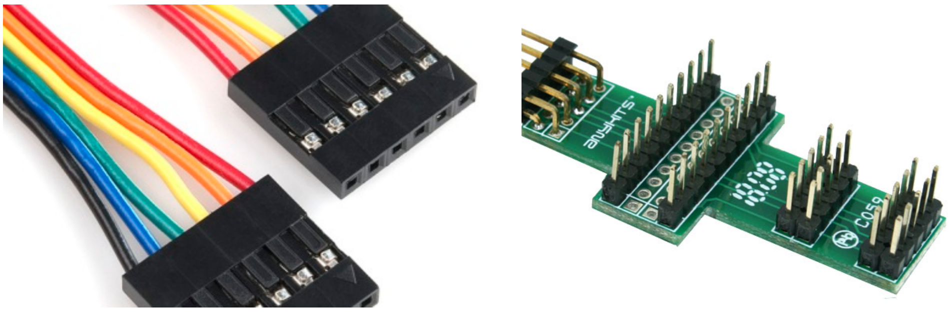


Figure 99 - Images of single-in-line connecting wires (Left) and single-in-line pins (Right).

To further reduce the risk of wire damage, the edges of the PCB will be sanded to remove any burrs. Despite the additional labour time, it will prevent the wires being cut if they contact the edges. Furthermore, it enables easier and safer assembly for the operative as the untreated PCB would be abrasive to hold and place in the kettle. The wires to different components such as the switches and heating thermistor are colour coded to ensure they are connected correctly.

To ensure the electronics would fit within the kettle base – a key specification point – a CAD check was performed. The PCB dimensions are 55.6mm x 60.9mm x 33.5mm, leaving ample room in the bottom casing which had an internal diameter of 120mm.

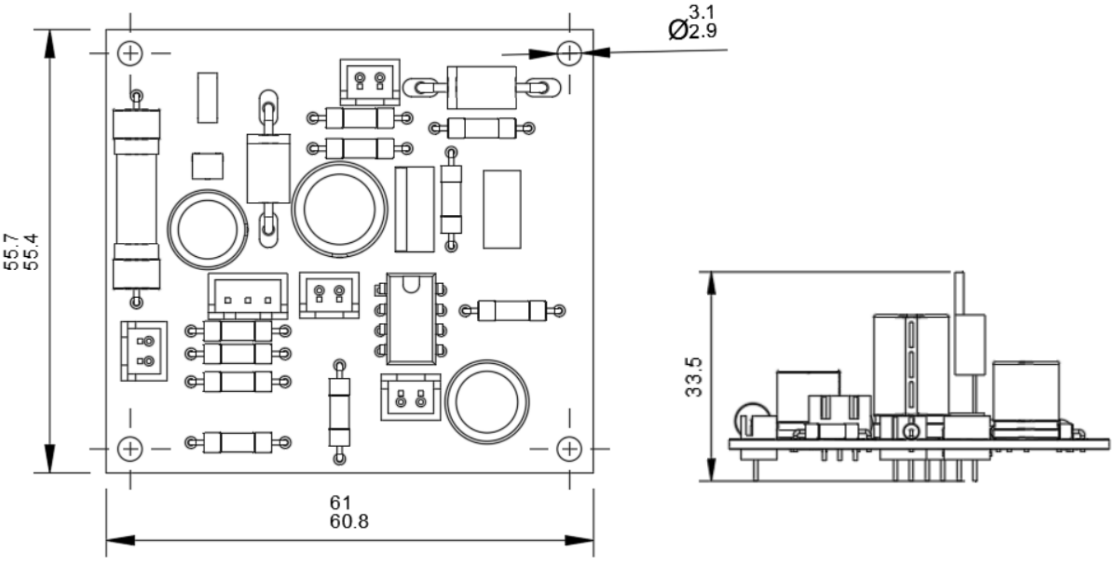


Figure 100 - PCB Drawing

5.4.3.1 Component Mounting

All the components placed on the PCB will be through-hole mounted. The advantages of through-hole over surface-mount technology are summarised in Table 24.

Table 24 - A comparison between surface-mount and through-hole technology [81].

Feature	Surface Mount Technology	Through-Hole Technology
Board Application	Low power	High power
Stress	May fail in high stress	Good for high stress
Manufacturing Cost	Less expensive at scale	More expensive in general
Board Layout Area	Double sided, small	Single-sided, large

As the PCB is for use in a household kettle, the operating conditions are uncontrolled; and a low stress environment is not guaranteed. The kettle is unlikely to be handled with the upmost care throughout its life, with the user forcefully placing it on a worktop, or dropping it. Whilst surface-mount devices are secured only by solder on the surface of the board, through-hole component leads run through the board, allowing the components to withstand greater environmental stresses. The main advantage of surface-mount technology for this application is the cost. For large scale manufacture, the cost can be between 30% to 50% cheaper. The assembly can be performed by pick-and-place robots with little need for human intervention, and there are fewer processes as no drilling is required. As the work would be outsourced to a specialist manufacturer, the higher initial overheads are not factor in this case.

The human element of through-hole is an advantage in situations such as this where environmental waste and product lifecycle are major considerations. Due to the precision of surface-mount technology, the PCB cannot be repaired or reworked easily, resulting in the PCB being scrapped in the case of a fault. To reduce the product's impact the global e-waste problem, faulty components will be repaired and re-sold.

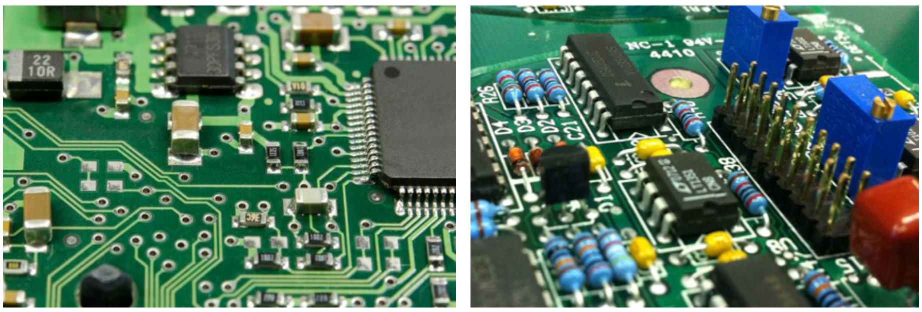


Figure 101 - Images of Surface Mount (Left) and Through-hole (Right) printed circuit boards.

5.4.3.2 Trace Dimensions

The PCB trace width determines the maximum current that can be passed through the circuit. A trace width that is too small would result in excessive heating which could damage the board or components. A balance must be achieved between the trace width being great enough to meet the current requirements, whilst making the board as compact and low cost as possible. For these reasons, determining the correct trace width is critical for meeting a number of specification points.

The minimum required trace area can be calculated using the following equation. The area calculated is in $mils^2$. (1 mil = 1/1000 of 1 inch = 0.0254mm)

Equation 2: PCB trace area

$$Trace\ Area = \left(\frac{Current}{K \times (Temperature\ Increase)^b}\right)^{\frac{1}{c}}$$

K = 0.048 (Temperature Constant)

b = 0.44

c = 0.725

The trace width can be calculated by dividing this value by the thickness, which in this case is 2.8mils. The required trace width for the high voltage rail is approximately 58mils, equivalent to 1.4mm. Using this trace width for the whole circuit would result in a circuit board that would not fit within the required space, as well as being more expensive due to the extra copper. Traces of 1.4mm would only be used for the higher voltage routes, the rest of the circuit will use 1.0mm width traces, highlighted below Figure 102.

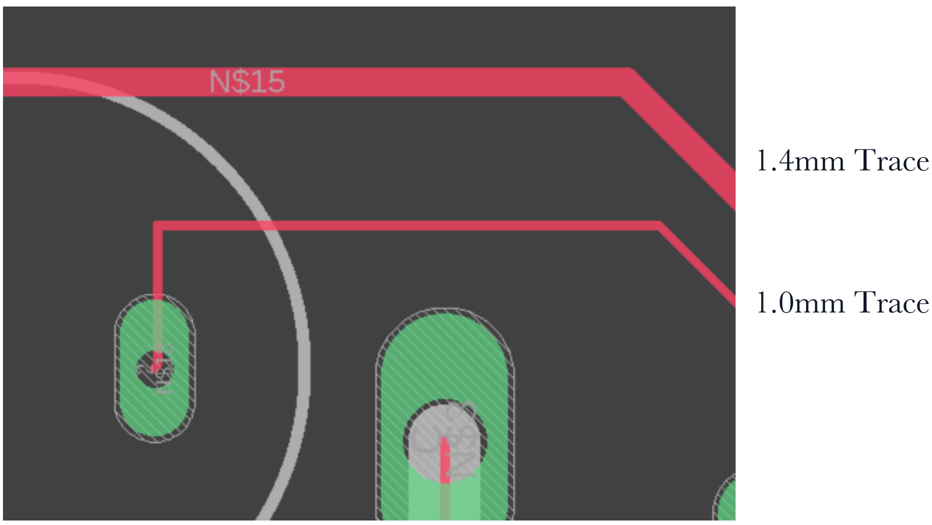


Figure 102 - A capture of the PCB design showing the two trace widths used.

5.4.3.3 Mounting

On the four corners of the PCB are the mounting holes. M3 self-tapping screws will be used to attach the PCB to the mounting brackets, which are fastened to the base. Although using an adhesive would be cheaper, the PCB would be susceptible to damage if in direct contact with the base, the contact surface of the kettle. As well as improved reliability, using this joining method further enables maintenance and the replacement of parts without damaging the kettle.

5.4.4 Heater Design

Given the kettle boiling chamber is vacuum lined and the presence of electronics under the container, a typical immersion heater is not feasible. Such elements also experience the build-up of limescale, reducing the heating efficiency.

The heating element will be situated on the underside of the bottom plate, transferring the thermal energy to the water through conduction. The construction is an electrical coil surrounded by an electrical insulator, all of which is covered by a steel casing. This can be seen in Figure 103.

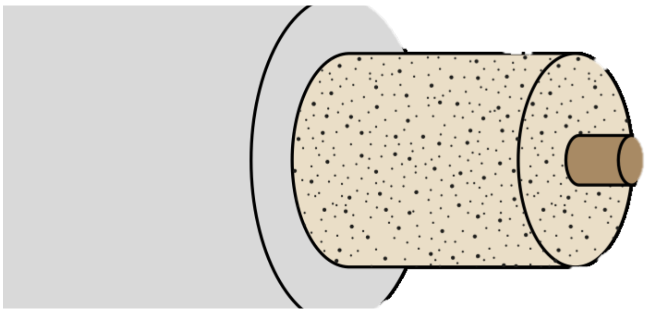


Figure 103 - A simplified cross-section of the heating element, showing the resistive wire, insulative layer, and outer casing.

The resistance wire will be made from Nichrome 80/20 (80% Nickel, 20% Chromium). It has a high resistance so offers good heating properties, and the Chromium forms an oxide layer when heated for the first time, preventing the ire from breaking [82].

The electrical insulator prevents the coil contacting the metal casing, creating a short circuit. The casing is made from AISI 304 stainless steel for its corrosion resistant properties and for being food safe [83]. The heating element will be purchased from an external supplier, reducing the manufacturing complexity for the company. The supplier will be chosen based on the quality of their product, the lead time of the orders, and the cost. From some initial research, the suppliers which can offer flexibility in design at low cost are based in China [84].

5.5 Manufacturing

The PCB will be chemically etched, allowing for large scale batch manufacturing. Line trials will be incorporated into the process, with extensive testing occurring to ensure product quality and functionality. As well as visual and fixture tests, the PCB will be placed in a jig to confirm the mounting hole placement. A further advantage of using through-hole technology rather than surface mount is that there is less of a need for X-ray inspection to check trace connections, a very costly process [85]. The tolerances on the PCB are common industry standards that should be replicable by the PCB manufacturer. These are highlighted in Table 25.

Table 25 - Tolerance of PCB manufacturing [86].

Description	**Tolerance**
PCB Thickness	+/- 10%
Hole Diameter	+/- 0.10mm
Hole Position	0.10mm
Copper Thickness	+/- 20μm
Trace Width	+/- 0.10mm

The electronic components will be assembled in Kenya with the product, with the PCB connections fitted just before product testing. At this stage, quality assurance checks will be performed on the PCB and peripheral components. The QA inspection will mainly target damaged parts or loose wires that have been mishandled during transportation. The advantage of purchasing electronics from China is the pre-existing infrastructure and expertise in the field. Sub-Saharan Africa has very limited knowledge in electronics, meaning the resulting product would be of a lower quality and likely more expensive [87].

5.6 Safety and Regulations

As this product must be CE certified to be sold within the EU, and meet other regulations to be sold in Kenya, various safety systems have been included [88]. The most important feature is the dry-boil protection, which prevents the user from operating the kettle with no or little water. Due to electronic complexity, the system on this device has double protection. The main component is a bi-metallic switch which breaks the circuit if the temperature exceeds a threshold. The metal plate inside which forms the electrical connection reforms once cooled.

The secondary system uses the thermistor. An additional line of code will be included to shut down the heating element if the resistance value of the transducer indicates a higher-than-expected temperature.

A further safety feature is the fuse which has been placed in series with the power connector. The sacrificial component will prevent any of the electronics being damaged and prevent an electrical fire in the case of a current surge. This is particularly important when the power supply used could be very temperamental and self-serviced.

5.7 Environmental Sustainability

5.7.1 E-Waste

E-waste is any electronics product that has reached the end of its useable life. As technology advances at a faster rate, the useable life of a product reduces, resulting in a faster production rate of e-waste [89]. Disposal to landfill and incineration are the most common methods of discarding e-waste.

Repairing and reusing electrical items is the best way to reduce electronic waste through lower rates of disposal and the subsequent lower production volumes that are required. The electronics for the kettle have been designed around this, with the use of single-in-line connectors for easy replacement of individual components, and through-hole mounting to enable repairs.

5.7.2 Restrictions of Hazardous Substances

The advancement of chemical and biological research has led to greater awareness of the dangers of certain substances to humans and the environment. The increase in e-waste resulted in greater restrictions on certain substances as the two main methods of disposal – landfill and incineration - result in the release of toxic substances. Table 26 shows sources of typical toxicants of e-waste present in electronic appliances and their adverse effects on humans.

Table 26 - Common sources of contamination in electronic components and the effect they have on humans.

Components	Sources	Effect on Humans	Reference
Mercury	Sensors, printed circuit boards	Chronic brain damage	[90] [91]
Lead	Printed circuit boards	Causes damage to nervous system and organs	[90] [91]

Cadmium	Switches, semiconductors	Respiratory problems	[90] [92]
Beryllium	Ceramic electronics	May cause lung cancer and skin diseases	[90] [91]
Arsenic	Transistors and printed circuit boards	Skin ailment, decreased nerve function, and lung cancer	[91]

In order to comply with the Restriction of Hazardous Substances Directive, and meet EU regulations, the kettle will be free from all banned substances, which include Mercury, Lead, and Cadmium. This will prevent the leaching of harmful compounds into eco-systems. One of the key components that is affected by the RoHS regulations is solder. Lead free solder is very common but offers reduced performance compared to the lead-based variant. To reduce the effects of using lead free solder, the copper will be plated with a mix of tin and silver. This coating is easier to solder and slows the rate of oxidation.

To ensure that the parts produced with suppliers meet these demands a Production Part Approval Process (PPAP) will be used, involving material emission and performance tests.

5.8 Cost

The two pie charts shown in Figure 104 demonstrate the cost breakdown for a prototype and production part. The test part cost was estimated using retailers such as RS Components, who offer fast delivery on high quality components. The production part cost was calculated from bulk order suppliers, often in China, who offer very low-cost parts with longer lead times. The total cost for the components was £29 and £7 for the prototype and production versions respectively.

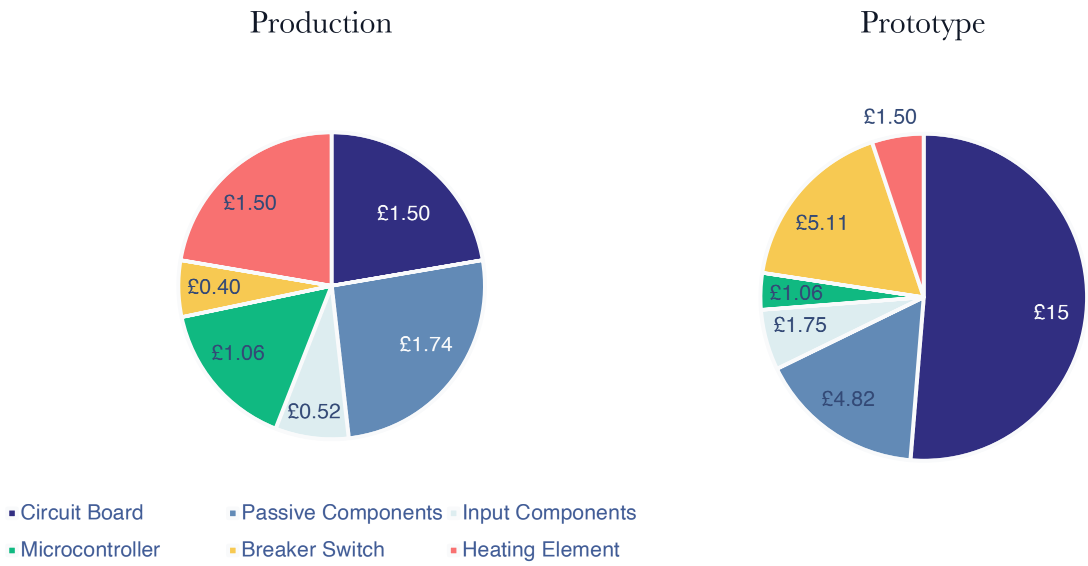


Figure 104 - Pie charts showing the cost distribution for a production and prototype part.

The biggest cost difference is between the printed circuit boards, with the prototype PCB costing approximately £15 compared to £1.50. The prototype PCB was quoted by a U.K. based supplier who specialise in unique parts or small sample batches. The advantage of using a manufacturer such as this for the prototype is the small lead time of 3 days, and it is easy to communicate designs and alterations. The large-scale manufacturing cost was taken from a Chinese supplier who handle large orders with delivery times of up to 60 days. Such an outfit would not be suitable for test parts, but the low cost and order quantity are ideal for mass production. A full cost breakdown can be found in Appendix E.

5.9 Design Review

5.9.1 DFMEA

A DFMEA has been performed to highlight the key risks with the circuit design, focussing on problems arising as a result from manufacturing, assembly, and operation. Each risk has been given a Risk Priority Number (RPN); equal to the product of the event severity, the event likelihood, and the likelihood of detection before release for sale. The potential failure modes have been assessed and extra precautions have been adopted to mitigate the risk, the subsequent RPN has been adjusted to reflect this. Figure 105 shows the key potential failure modes, quantifying the risk mitigation.

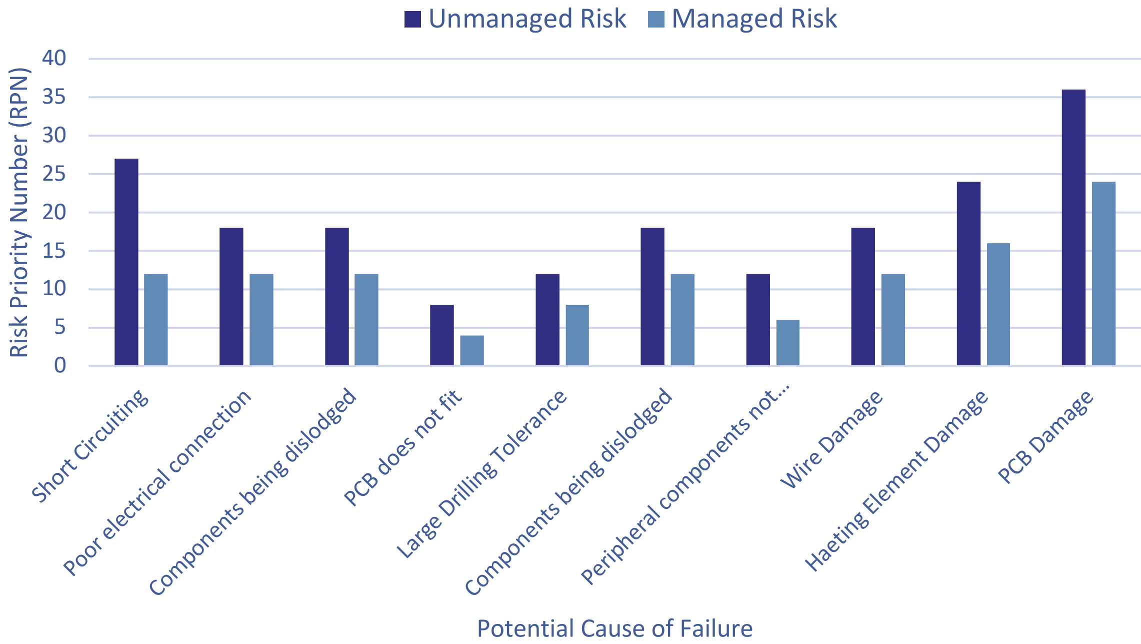


Figure 105 - The key DFMEA risks with the corresponding RPN pre and post mitigation.

5.9.2 Future work

The next stage of the electronics design involves creating the code off which the microcontroller can operate as intended. This will allow circuit simulation software to confirm the theory of operation before time and money is spent creating physical test parts. A breadboard of the major components will be made to test the code and the electronic theory.

During the physical prototyping phase of the design, the thermistor will need to be calibrated. Approximate values for the resistance at the threshold temperatures can be obtained through the resistance curve, but repeatable tests will need to be completed to confirm the results. The kettle electronics will have to undergo safety testing, including regulator tests.

5.9.3 Design Limitations

As previously mentioned, the inclusion of a dry-boil protection switch is an important safety feature, however, the lack of a mechanical device is a potential safety concern. A conventional kettle uses a bi-metallic switch which mechanically resets once the temperature, often of steam, reaches a certain threshold. If there is a fault with the switch, the user would be able to turn the kettle off. In this design, the switch is an electrical one connected in series with the heating element. If the switch or circuit failed, the heating element would remain on. The reason for this is the vacuum layer renders the use of mechanical devices near impossible. A potential solution could be to have two bi-metallic switches, in the case of one failing. It would be advisable to also include a line of code that allows the heart to be switched off if the power button is pressed mid operation.

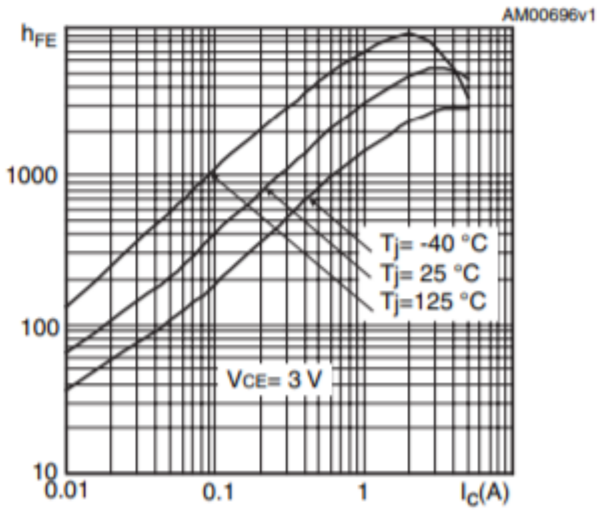


Figure 106 - Current gain characteristics of a TIP122 transistor at varying temperatures [93].

Another concern is the heat emitted by the electronics. Alongside the heating element radiation, the bottom casing is likely to get very hot, possibly compromising the component efficiency and operability. It also poses a risk to the integrity of the polypropylene casing. Figure 106 shows the current gain for a TIP122 transistor at 3V for varying temperatures. As the temperature increase, the current gain reduces for equivalent gain (h_{FE}) values.

A method of mitigating the problem would be incorporating a heat shield under the heating element, blocking heat from being dissipated downwards. This would also increase the kettle efficiency as more of the thermal energy would be directed towards the water. Designing slots in the bottom casing would also be beneficial, although this would allow contaminants into the electronics, creating a flow of air would remove some heat.

5.9.4 Design Specification Evaluation

Table 27 - Circuit Design Specification Evaluation

Requirement	Target	Must/Wish	Achieved	Justification
Power Source	Powered by 12V DC	Must	Achieved	The circuit is powered by 12V.
Lifespan	Have a lifetime of 10,000 boil cycles	Must	Achieved	All components have been selected to meet minimum cycles.
Boil Time	Boil time for 1L of water should be under 20 minutes	Wish	Partially Achieved	For input powers of >300W, this has been achieved.

Water Quality	Improve quality of water through water temperature exceeding 65°C for 1 minute	Must	Achieved	The two heating modes provide the user with the option to sterilise rather than boil the water.
Cost	Heater and electronics cost within £10	Must	Partially Achieved	The total component cost is below £10, including transport and manufacturing the total amortised cost would be higher.
Size	Compact PCB that fits in kettle base	Must	Achieved	The PCB and heating element fit within the bottom casing.
Strength	Components and connections are robust	Must	Partially Achieved	Through-hole mounting was used for the PCB components, to improve the strength the omission of the PCB would be required.
Maintenance	Easy access to key components for repair	Wish	Achieved	The PCB has been designed with screw mountings to enable removal.

5.10 Conclusion

In this report, an electronic circuit was designed to heat water through a resistive heating element using power from a DC solar home system. Efficiently heating water using low input power is a challenge, slow boil times allow for greater heat loss during the boiling process, reducing the thermal efficiency. A major part of this design task was boosting the current provided by the 12V battery, which in this case, was achieved using a TIP122 Darlington pair transistor in a common gain configuration. A balance had to be found between maximising current gain, whilst maintaining a low cost for the product, which was for use in less developed regions where retail price is a driving factor. To increase the efficiency, a second heating mode was included that sterilises the water at 70°C rather than 100°C, allowing the saved electricity to be used with other appliances. Although the inclusion of a microcontroller adds cost, it provides scope to make operational improvements on later models without changing the design. The total cost of the production PCB is £7, lower than the £10 quoted in the design specification. However, once the cost of transportation from China has been amortised it will increase marginally.

6 Project Proposal and Review

Figure 107: Render of the final design

6.1 Solution Specification

Specification Point	Value	Source
Maximum Power Source	DC	Brief
Voltage Rating	12V	PCB Report
Max Power Rating	300W	PCB Report
Dimensions	283mm, 176mm, 146mm	CAD
Volume	1.5L (Boiling chamber) 0.75L (Top chamber)	CAD
Efficiency	~85% for 300W	MATLAB
Boiling Time	1.5L in 18 mins (70°C at 300W) 1.5L in 31 mins (100°C at 300W)	MATLAB
Filtering Time	1:30 mins (1.5L)	Filter Report
Total Cycle Time	1.5L in 33 mins (100°C at 300W)	
BoM Cost	£16.59	BoM
Materials	Stainless Steel 304 Polypropylene Polyester 120 mesh Cork	
Sustainability	All materials recyclable (excluding PCB)	
Life Cycle	10,000 cycles (Kettle) 70 cycles (Filter)	
Operation	One handed	
Safety	Steam release Dry boil	
Modes	70°C and 100°C	

Boiling time and efficiency have been calculated using the MATLAB simulation mentioned in the earlier section, there is a large amount of error with this as there are many factors that it does not consider. They also both are functions of input power and have been stated at the best-case scenario with 300W. For comparison at 150W it would take 63 mins to boil to 100°C.

6.2 Operating Sequence

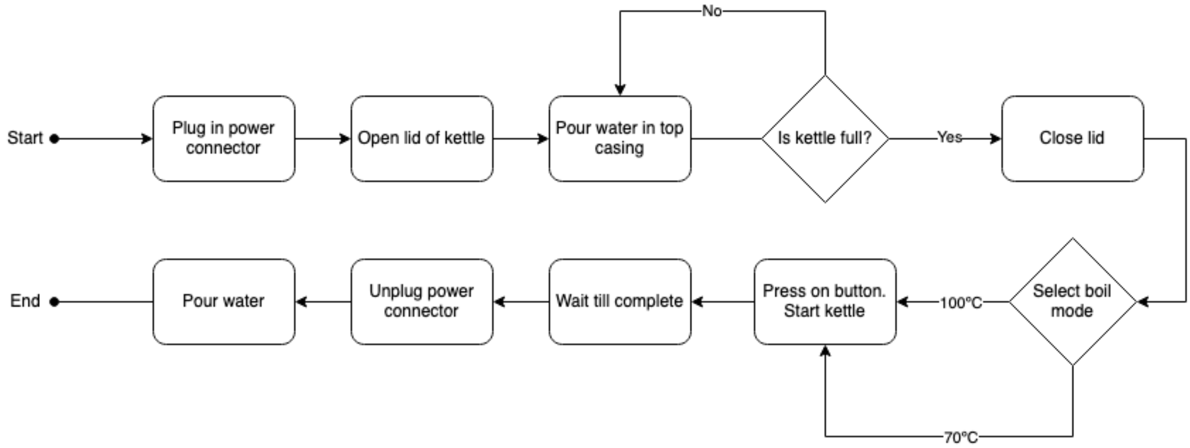


Figure 108: Operating sequence of the kettle

6.3 Bill of Materials

The total BoM cost of the kettle is £16.59, with the full BoM shown in Table 28.

Table 28: Bill of materials for kettle

Component	Material	Quantity	Cost (£)	Total Cost (£)
Handle Grip	Cork	1	0.8400	0.840
Stainless Steel Sheet	Stainless Steel 304	2	0.78/kg	1.490
Wires	Electrical Wire	9	0.042/m	0.039
Momentary On Switch	N/A	1	0.2800	0.280
Rocker Switch	N/A	1	0.0710	0.071
Nuts, Bolts and Plastic rivets	Steel and plastic	24	0.0071	0.240
PCB Mounting feet	Plastic	4	0.0099	0.040
Plug	N/A	2	0.4930	0.990
Cable	N/A	1	0.042/m	0.042
Crocodile Clips	N/A	2	0.0990	0.198
Stainless Steel Mesh	Stainless Steel 304	2	0.1620	0.324
Polyester Mesh	Polyester	2	0.0068	0.014
Stainless Steel Mesh	Stainless Steel 304	4	0.4690	1.876
Lid O-Ring	Silicone Rubber	1	0.2500	0.898
Cartridge O-Ring	Silicone Rubber	1	0.3000	0.898
Circuit Board	N/A	1	1.5000	1.500
Single-In-Line Connectors 2 Pin	N/A	1	0.8000	0.800
Single-In-Line Connectors 3 Pin	N/A	1	0.2000	0.200
7805 Voltage Regulator	N/A	1	0.0800	0.080
Fuse	N/A	1	0.0600	0.060
Inductor	N/A	1	0.1500	0.150
Resistor	N/A	1	0.0500	0.050

470μF Capacitor	N/A	1	0.0500	0.050
1000μF Capacitor	N/A	1	0.0500	0.050
Diode	N/A	1	0.1800	0.180
SPST Momentary Switch	N/A	1	0.2800	0.280
SPDT Rocker Switch	N/A	1	0.0700	0.070
NTC Thermistor	N/A	1	0.1700	0.170
ATTINY85-20PU Microcontroller	N/A	1	1.0600	1.060
TIP122 Transistor	N/A	1	0.1200	0.120
Breaker Switch	N/A	1	0.4000	0.400
Heating Element	N/A	1	1.5000	1.500
Spring	Spring Steel	1	0.0100	0.010
Handle	Polypropylene	1	0.0621	0.062
Cartridge Body	Polypropylene	1	0.0745	0.075
Bottom Cartridge Snap	Polypropylene	1	0.0121	0.012
Lid Top Snap	Polypropylene	1	0.0105	0.010
Lid Bottom Snap	Polypropylene	1	0.0126	0.013
Base	Polypropylene	1	0.5433	0.543
Base bottom	Polypropylene	1	0.1825	0.183
Latch Button	Polypropylene	1	0.0042	0.004
Latch Bracket Hinge	Polypropylene	1	0.0009	0.001
Latch Hinge	Polypropylene	2	0.0004	0.001
Latch	Polypropylene	1	0.0027	0.003
Latch Mechanism Link	Polypropylene	2	0.0023	0.005
Latch Mechanism Holder	Polypropylene	1	0.0186	0.019
Latch Lid	Polypropylene	1	0.0663	0.066
Lid Hinge	Polypropylene	1	0.0009	0.001
Spout Casing	Polypropylene	1	0.5140	0.514
Lid Top Part	Polypropylene	1	0.1071	0.107

6.4 Manufacturing Costs

The manufacturing costs for small-scale and large-scale operations are shown below, not including site rental costs. Warehouses in Kenya charge a monthly average of £3.21 per m^2; approximately £3,200 per month for small scale manufacturing and £14,400 per month for large scale manufacturing [94].

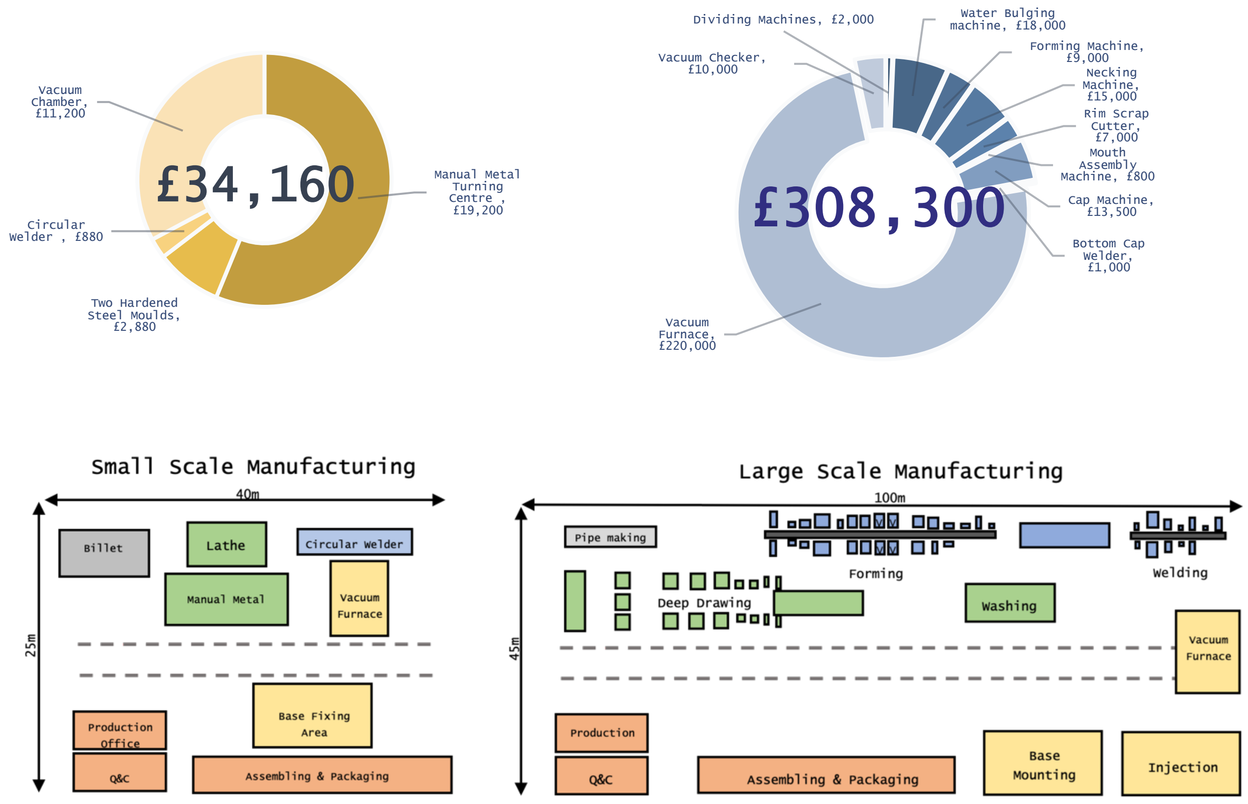


Figure 109: Cost estimates for manufacturing plants at small and large scale production.

6.5 Logistics and Supply Chain

Our kettle would best suit an indirect sales approach where we would sell to local distributers, who would then sell to the final user. Local distributors such as Copia provide delivery, mobile payment, tracking, returns and a network of sales agents to target middle and low-income customers [95]. This will allow for successful distribution without the need for a fully integrated direct sales approach. The added trust in an established distributer would also increase adoption of our kettle.

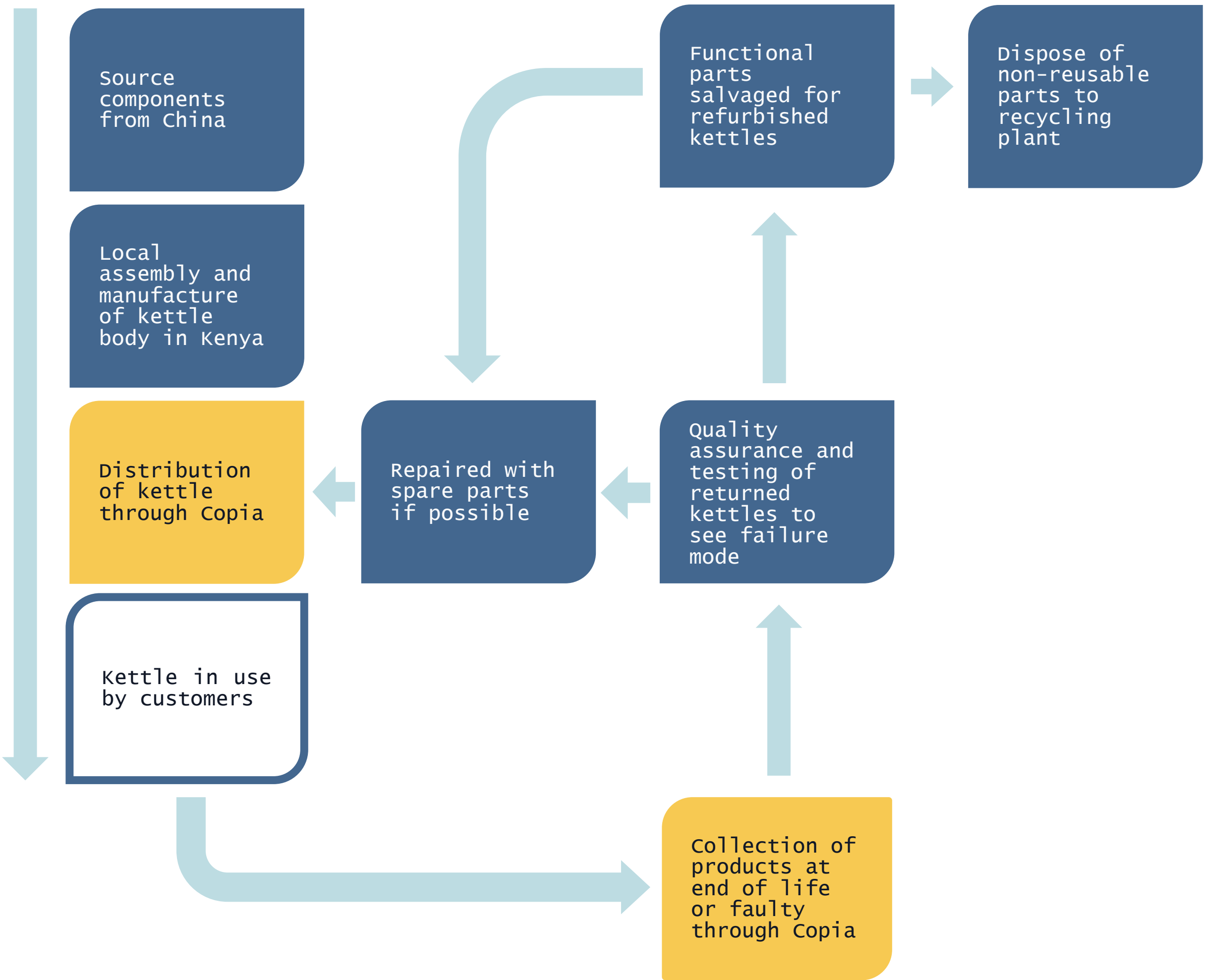


Figure 110: Diagram showing product lifecycle and logistics.

6.6 Product Lifecycle

All of the body materials are recyclable, reducing the likelihood that the product will end up as landfill. To prevent unnecessary e-waste, components can be repurposed and salvaged before the rest of the kettle is recycled. In the case of a faulty appliance, refurbishment would be explored first, allowing it to be resold at a lower price. The product packaging will be primarily cardboard, with few or no polyethene bags, further reducing the environmental impact.

6.7 Maintenance and Serviceability

Since there are minimal permanent joints on the kettle, all injection moulded plastic parts can be replaced should they get damaged. This minimises waste and allows for local and unskilled repair of the kettle. The filter contents that need to be replaced is also easily done by the user with minimal wasted parts.

6.8 Review

Table 29 lists each requirement from the PDS to see if the design meets the criteria.

Table 29: Review of PDS criteria.

Requirement	Met?
Fast cycle time	Yes
Fast boil time	Yes
Filter time	Yes
Weight	Yes
Energy efficient	Yes
Heat water to safe temperature	Yes
Remove harmful contaminants	Yes
Stable	Yes
Locally manufactured	Yes
Safe	Yes
Affordable	Yes
Product must have a long lifetime	Yes
Easy to repair	Yes
Easy to use	Yes
Large boiling chamber capacity	Yes
Large filter chamber capacity	No
Multiple power connectors	No

The large filter chamber capacity requirement was not able to be met as it would have compromised the product being easy to use. Having a 1.5L top chamber volume would have made the kettle far too large. Likewise, having multiple power connectors was not achieved. This was because it would have created more e-waste and potentially unnecessary parts. Instead creating a specification of the power cable assembly was preferred.

6.9 Limitations

Due to the design decisions the design has a few limitations that were not able to be fully mitigated. The fill window is small and cumbersome to use, it is also impossible to see it from outside. The top chamber also is only half the full volume of the kettle, meaning you would have to fill the top chamber twice to boil the kettle at full capacity; this is not ideal in terms of usability.

6.10 Conclusion

The brief set out the task of designing a super-efficient DC appliance, with a potential maximum efficiency of 85%, the project can be seen to be a success in that regard.

6.10.1 Further Work

As part of the user centred design process, prototyping, studying a person using the prototype and iterating is crucial in ending up with well-designed product. The next steps could be to create a physical working prototype with 3D printed parts instead of injection moulded to experiment with and test. This way the actual efficiency could be measured instead of relying on simulations. A more comprehensive thermal model or CFD simulation could be beneficial in optimising the efficiency of the kettle as well.

There is still scope for a further cost reduction for this product. On top of the efforts that have already been made, additional work in reducing manufacturing processes, decreasing mould complexity and part count could see the overall BoM cost of the kettle to reduce significantly.

Redesigning the electronics to be passive would also remove the need for a microcontroller and would make the kettle cheaper.

6.10.2 Reflection

Overall, the project has been successful in designing a super-efficient kettle for Kenya, given the resources and time available. Externally, we hope to succeed in the EfA design challenge, looking forward to the grand final in July.

7 References

[1] United Nations, "THE 17 GOALS," United Nations, 2021. [Online]. Available: https://sdgs.un.org/goals. [Accessed 27 4 2021].

[2] IEA, "SDG7: Data and Projections," IEA, Paris, 2020.

[3] C. Everist, L. Evason, N. Wan and L. Peacock, "Business Case Report," University of Bath, 2021, Bath.

[4] C. Everist, L. Evason, N. Wan and L. Peacock, "Technical Feasability Report," University of Bath, Bath, 2021.

[5] "Global Off Grid Solar Market Report H1 2020," GOGLA, 2020. [Online]. Available: https://www.gogla.org/sites/default/files/resource_docs/global_off_grid_solar_market_report_h1_2020.pdf. [Accessed 2021 5 1].

[6] AliExpress, "Car Hot Kettle Portable Water Heater Travel," AliExpress, [Online]. Available: https://www.aliexpress.com/item/1005001592769939.html?spm=a2g0o.productlist.0.0.4e3612d8u5iLoN&algo_pvid=51be8282-b180-4876-ad76-3d5e9203bedc&algo_expid=51be8282-b180-4876-ad76-3d5e9203bedc-9&btsid=0b0a555616215068604595867e4dc0&ws_ab_test=searchweb0_0,se. [Accessed 05 2021].

[7] AZOM, "Medical Applications of Stainless Steel 304 (UNS S30400)," AZOM, [Online]. Available: https://www.azom.com/article.aspx?ArticleID=6641. [Accessed 05 2021].

[8] teamstainless, "The Global Life Cycleof Stainless Steels," ISSF, 2015.

[9] Kenyan Standard, "KS277:1980," KS, Nairobi, 2015.

[10] N. Wan, "Techanical Feasibility - Filter," University of Bath, Bath, 2021.

[11] WORLD HEALTH ORGANIZATION 2018, "KENYA: DIARRHOEAL DISEASES," WORLD HEALTH RANKINGS, 2018. [Online]. Available: https://www.worldlifeexpectancy.com/kenya-diarrhoeal-diseases#:~:text=Kenya%3A%20Diarrhoeal%20diseases&text=According%20to%20the%20latest%20WHO,Kenya%20%234%20in%20the%20world.. [Accessed 17 May 2021].

[12] G. O. Achieng, V. O. Shikuku, D. M. Andala, G. M. Okowa and J. J. Owuor, "Assessment of water quality of the Nyando River (Muhoroni-Kenya) using the water quality index (WQI) method," *International Research Journal of Environmental Sciences,* vol. 8, no. 2, pp. 27-33, 2018.

[13] P. H. J. S. B. K. Winfred Kilonzo, "The Storage and Water Quality Characteristics of Rungiri Quarry Reservoir in Kiambu, Kenya, as a Potential Source of Urban Water," *Hydrology,* vol. 6, no. 4, p. 94, 2019.

[14] E. Ochungo, G. Ouma, J. Obiero and N. Odero, "Water Quality Index for Assessment of Potability of Groundwater Resource in Langata Sub County, Nairobi-Kenya," *American Journal of Water Resources,* vol. 7, no. 2, pp. 62-75, 2019.

[15] Kenya Bureau of Standards, KENYA STANDARD: Potable water - Specification, 1 ed., Nairobi: Kenya Bureau of Standards, 2015.

[16] BOYD CORPORATION, "How Hot is too Hot? The Real Maximum Temperature of Your Product," BOYD CORPORATION, 2021. [Online]. Available: https://www.boydcorp.com/resources/resource-center/blog/237-maximum-touch-temperature.html. [Accessed 20 May 2021].

[17] BRITA, "BRITA Maxtra+ Universal Water Filter Cartridge, Pack of 6," John Lewis, 2021. [Online]. Available: https://www.johnlewis.com/brita-maxtra-universal-water-filter-cartridge-pack-of-6/p3289971?sku=237072526&s_ppc=2dx92700055675268747&tmad=c&tmcampid=2&gclid=Cj0K

CQjw7pKFBhDUARIsAFUoMDYVnhlynvTlY-BtSN9a6IBUYVoucu400VWkLKxL9noXCxzElNxMqaQaAgsDEALw_wcB&gclsrc. [Accessed 19 May 2021].

[18] BRITA, "BRITA MAXTRA+ water filter cartridges 3 pack," BRITA, 2021. [Online]. Available: https://www.brita.co.uk/water-filter-system/water-filter-cartridges/maxtra-plus-pack-3-cartridges . [Accessed 6 May 2021].

[19] K. Barrington, "USING CARBON IN A FRESHWATER AQUARIUM," RATE MY FISH TANK, 29 January 2014. [Online]. Available: https://www.ratemyfishtank.com/blog/using-carbon-in-a-freshwater-aquarium#:~:text=It%20is%20typically%20recommended%20that,become%20deactivated%20after%20this%20time.. [Accessed 8 May 2021].

[20] Pure Water Products, LLC, "Does Activated Alumina Add Aluminum to the Water It Treats?," Pure Water Products, LLC, 27 September 2006. [Online]. Available: https://www.purewaterproducts.com/articles/activated-alumina#:~:text=The%20total%20amount%20of%20aluminium,for%20drinking%20water%20%5B8%5D.. [Accessed May 6 2021].

[21] M. Vithanage and P. Bhattacharya, "Fluoride in Drinking Water: Health Effects and Remediation," in *: CO2 Sequestration, Biofuels and Depollution*, Switzerland, Springer International, 2015, pp. 105-151.

[22] X. Zeng, J. Xia, Z. Wang and W. Li, "Removal of iron and manganese in steel industry drainage by biological activated carbon," *Desalination and Water Treatment,* vol. 56, no. 9, pp. 2543-2550, 22 August 2015.

[23] FilterBag, "Filter Media," FilterBag, ` 2021. [Online]. Available: https://www.filterbag.com/Filter-Media-20.html. [Accessed 11 May 2021].

[24] T. Sachdev, T. Kate and S. Gauri, "Nylon vs. Polyester," Diffen, 2015. [Online]. Available: https://www.diffen.com/difference/Nylon_vs_Polyester. [Accessed 11 May 2021].

[25] M. Gulden, "304 vs 316 Stainless Steel," Boulder Engineering Studio, 16 February 2017. [Online]. Available: https://www.boulderes.com/resource-library/304-vs-316-stainless-steel. [Accessed 20 May 2021].

[26] The Engineering Toolbox, "Convective Heat Transfer," The Engineering Toolbox, 2003. [Online]. Available: https://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html. [Accessed 17 May 2021].

[27] G. W. Philip Kosky, Convection Heat Transfer Coefficient, Science Direct, 2021.

[28] Olefins & Polymers USA, "Polypropylene Processing Guide," 2021. [Online]. Available: https://www.ineos.com/globalassets/ineos-group/businesses/ineos-olefins-and-polymers-usa/products/technical-information--patents/ineos_polypropylene_processing_guide.pdf. [Accessed 18 May 2021].

[29] X. Z. C. L. J. P. S. L. L. Z. C. L. Aiyuan M, "Study on regeneration of spent activated carbon by using a clean technology," Online, 2017.

[30] A. R. Rabia, A. H. Ibrahim and N. N. Zulkepli, "Activated alumina preparation and characterization: The review on recent advancement," *E3S Web of Conferences,* vol. 34, no. 02049, p. 8, 2018.

[31] Enviromental XPRT, "activated carbon Companies in Kenya," Enviromental XPRT, 2021. [Online]. Available: https://www.environmental-expert.com/companies/keyword-activated-carbon-871/location-kenya. [Accessed 16 May 2021].

[32] R. Leblanc, "An Overview of Polypropylene Recycling," The Balance Small Business, 9 May 2019. [Online]. Available: https://www.thebalancesmb.com/an-overview-of-polypropylene-recycling-2877863#:~:text=Products%20made%20of%20PP%20degrade,such%20as%20lead%20and%20cadmium.. [Accessed 16 May 2021].

[33] P. Mpungu, “Despite pioneering ban, Kenya is drowning in single-use plastic,” ALJAZEERA, 4 December 2020. [Online]. Available: https://www.aljazeera.com/economy/2020/12/4/despite-pioneering-ban-kenya-is-drowning-in-single-use-plastic#:~:text=The%20shortfall%20is%20staggering.,the%20plastic%20waste%20it%20produces.. [Accessed 16 May 2021].

[34] EARTH HERO, “Silicone: The Plastic Alternative,” EARTH HERO, 15 October 2018. [Online]. Available: https://earthhero.com/silicone-the-plastic-alternative/. [Accessed 16 May 2021].

[35] United Silicones, “How Long Should Silicone Sealant Last Around Your Home,” United Silicones, 18 September 2014. [Online]. Available: https://www.united-silicones.com/blog/how-long-should-silicone-sealant-last-around-your-home/. [Accessed 16 May 2021].

[36] B. P. LIMITED, “Kettle with lid damping mechanism”. NSW, Australia Patent 9456714, 04 Oct 2016.

[37] M. Reiner, “The teapot effect…a problem,” Israel Institute of Technology, Haifa, 1956.

[38] “Contraction of Plastics Molded Part,” SpecialChem SA, 2017. [Online]. Available: https://omnexus.specialchem.com/polymer-properties/properties/shrinkage . [Accessed 19 05 2021].

[39] “Pass-through coring images,” Novocom, 2021. [Online]. Available: https://novocom.top/view/f113cc-mold-undercut/ . [Accessed 18 05 2021].

[40] “Factory Price Carbon Steel Tension Spring Corrosion Resistance and Durability Furniture Hardware Sofa Spring Unit,” Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/Factory-Price-Carbon-Steel-Tension-Spring_1600227479749.html?spm=a2700.galleryofferlist.normal_offer.d_title.74f65787R4lV8y&s=p . [Accessed 17 05 2021].

[41] “Hengsheng stainless steel customized torsion spring,” Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/Hengsheng-stainless-steel-customized-torsion-spring_60689136446.html?spm=a2700.galleryofferlist.topad_creative.d_image.4a794386a9W77W . [Accessed 17 05 2021].

[42] “T015-090-062-R Torsion Springs,” Raymond, 2021. [Online]. Available: https://www.assocspring.co.uk/torsion-springs/T015-090-062-R . [Accessed 17 05 2021].

[43] I. Boustead, “Eco-profiles of the European Plastics Industry,” PlasticsEurope, Auderghem, Brussels, 2005.

[44] “HOW MUCH MORE EFFICIENT CAN INJECTION MOULDING MACHINES GET?,” Tex Plastics, 27 05 2019. [Online]. Available: https://www.tex-plastics.co.uk/moulded-plastic-parts/2019/05/27/how-much-more-efficient-can-injection-moulding-machines-get. [Accessed 18 05 2021].

[45] L. Peacock, P. Lavender-Jones, C. Everist, L. Evason and N. Wan, “Technical Feasibility Study,” University of Bath, 2020.

[46] Sunglory, “Double wall stainless steel vacuum flask machine vacuum furnace for stainless steel vacuum flask water bottle making machines,” Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/1600244702458-804372636/double_wall_stainless_steel_vacuum_flask_machine_vacuum_furnace_for_stainless_steel_vacuum_flask_water_bottle_making_machines.html?spm=a2700.shop_plgr.41413.9.628d36d0hoclh8. [Accessed 2021 05 19].

[47] “Kinox Thermal Electric Kettle. 1 Litre 360° Cordless 1200 W,” Amazon, 2021. [Online]. Available: https://www.amazon.co.uk/Kinox-Thermal-Electric-Kettle-Cordless/dp/B08TY6HFZF/ref=pd_lpo_79_t_0/258-8746842-5585002?_encoding=UTF8&pd_rd_i=B08TY6HFZF&pd_rd_r=b82a9db2-1650-4b7e-ad53-a504813eef90&pd_rd_w=jBDc0&pd_rd_wg=IPqas&pf_rd_p=e0b512b6-8cc4-4ac5-840d. [Accessed 19 05 2021].

[48] Ryerson, "Corrosion Resistance: A (Stainless) Family Affair," 13 10 2018. [Online]. Available: https://www.ryerson.com/resource/the-gauge/stainless-steel-families. [Accessed 05 19 2021].

[49] British Stainless Steel Association, "SELECTION OF STAINLESS STEELS FOR THE FOOD PROCESSING INDUSTRIES," BSSA, 2012. [Online]. Available: https://bssa.org.uk/bssa_articles/9-selection-of-stainless-steels-for-the-food-processing-industries/. [Accessed 19 05 2021].

[50] Engineering Toolbox, "Fluid Heat Transfer Coefficients," 2003. [Online]. Available: https://www.engineeringtoolbox.com/overall-heat-transfer-coefficients-d_284.html. [Accessed 19 05 2021].

[51] Engineering Toolbox, "Emissivity Coefficient Materials," 2003. [Online]. Available: https://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html. [Accessed 19 05 2021].

[52] Health and Safety Executive, "Scalding and Burning," [Online]. Available: https://www.hse.gov.uk/healthservices/scalding-burning.htm. [Accessed 19 05 2021].

[53] RS Components, "RS PRO Compact Power Connector Plug, 2P, 40A, 500 V dc," RS Components, 2021. [Online]. Available: https://uk.rs-online.com/web/p/compact-power-connectors/1805399/. [Accessed 19 05 2021].

[54] RS Components, "RS PRO Compact Power Connector Socket, 2P, 40A, 500 V dc," RS Components, 2021. [Online]. Available: https://uk.rs-online.com/web/p/compact-power-connectors/1805398/. [Accessed 19 05 2021].

[55] RS Components, "Single Pole Double Throw (SPDT) Momentary Blue LED Push Button Switch," 2021. [Online]. Available: https://uk.rs-online.com/web/p/products/8114110?cm_mmc=en-ds-_-mcad-_-traceparts-_-8114110. [Accessed 19 05 2021].

[56] RS Components, "Single Pole Double throw (SPDT), (On)-Off-(On) Rocker Switch," 2021. [Online]. Available: https://uk.rs-online.com/web/p/rocker-switches/7932550/. [Accessed 19 05 2021].

[57] REX Plastics, "How Much Does Plastic Injection Molding Cost?," REX Plastics, 2013. [Online]. Available: https://rexplastics.com/plastic-injection-molds/how-much-do-plastic-injection-molds-cost. [Accessed 19 05 2021].

[58] Stratasys, "Three Mistakes to Avoid when Designing for Injection Molding," Stratasys, 2021. [Online]. Available: https://www.stratasysdirect.com/technologies/injection-molding/injection-molding-design-mistakes. [Accessed 19 05 2021].

[59] Engineering Plastic Co., "Polypropylene pellet cost," Alibaba, 2021. [Online]. Available: https://shqishen.en.alibaba.com/productgrouplist-816468643/PP.html?spm=a2700.details.0.0.1070105c9EPARP. [Accessed 19 05 2021].

[60] Alibaba, "House wiring flexible pvc jacket," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/House-wiring-flexible-pvc-jacket-H07V_60771072213.html?spm=a2700.galleryofferlist.topad_classic.d_title.be9178ff2vZQz9. [Accessed 19 05 2021].

[61] Alibaba, "16mm high head momentary black dual led 24V illuminated push button switch," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/16mm-high-head-momentary-black-dual_62408697694.html?spm=a2700.galleryofferlist.normal_offer.d_title.485b63d5LYV3Ul. [Accessed 19 05 2021].

[62] Alibaba, "on off on spdt round boat rocker switch," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/3-pins-3-way-on-off_1600061769227.html?spm=a2700.13765215.0.0.83da3615wz0BGG. [Accessed 19 05 2021].

[63] Alibaba, "DIN 934 SS m3 m5 m7 m15 hex nut," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/DIN-934-SS-m3-m5-m7_62442965198.html?spm=a2700.themePage.5238101001485.89.1b12233dHGeHii. [Accessed 19 05 2021].

[64] Alibaba, "DIN 7991 countersunk head cap screws Grade 10.9 Zinc Plated High Tensile Strength Countersunk Bolts M2 M3 M4 M5 M6 M8 M10," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/DIN-7991-countersunk-head-cap-screws_62260481131.html?spm=a2700.galleryofferlist.normal_offer.d_title.63681143D65ORe. [Accessed 19 05 2021].

[65] Alibaba, "R2024/R3035/R4060 Natural Plastic Nylon Rivet Push Rivets," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/R2024-R3035-R4060-Natural-Plastic-Nylon_60828092099.html?spm=a2700.galleryofferlist.normal_offer.d_title.4e495d66YKau95. [Accessed 19 05 2021].

[66] Alibaba, "cm L shape PCB Mounting Feet with Screw for Arcade Gaming Board electronic parts L Type PCB board white plastic feet," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/2cm-L-shape-PCB-Mounting-Feet_1600181644380.html?spm=a2700.galleryofferlist.normal_offer.d_title.22651446dpWtH4. [Accessed 19 05 2021].

[67] RS Components, "RS PRO 5 Core 6 mm² Mains Power Cable, Black CPE Sheath 100m, 45 A 450 V, 750 V, H07RN-F," 2021. [Online]. Available: https://uk.rs-online.com/web/p/electrical-mains-power-cables/7739092/. [Accessed 19 05 2021].

[68] Alibaba, "JIALUN Copper plated Steel 100Amp Alligator Clips Heavy Duty Crocodile Clips," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/JIALUN-Copper-plated-Steel-100Amp-Alligator_1600208795700.html?spm=a2700.galleryofferlist.normal_offer.d_title.3c7222a1BKV06s&s=p. [Accessed 19 05 2021].

[69] Alibaba, "CNC Pillar Drilling Machine EDM Drilling Machine Price BH703," Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/CNC-Pillar-Drilling-Machine-EDM-Drilling_60822374313.html?spm=a2700.galleryofferlist.normal_offer.d_image.28c2661enICzqk&s=p. [Accessed 19 05 2021].

[70] Alibaba, "Pipe making machine flask machine for making water bottle," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/1600225291738-804372636/Pipe_making_machine_flask_machine_for_making_water_bottle.html?spm=a2700.shop_plgr.41413.26.8c4d6760fcSayd. [Accessed 19 05 2021].

[71] Alibaba, "Steel pipe cutting machine,bottle making machine,flask machine-Sun Glory Industry," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/62111517816-804372636/Steel_pipe_cutting_machine_bottle_making_machine_flask_machine_Sun_Glory_Industry.html?spm=a2700.shop_plgr.41413.21.27b76c50CMjE5V. [Accessed 19 05 2021].

[72] Alibaba, "Stainless Steel water bottle thermos flask kettle coffee pot making hydroforming machine water bulging machine," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/62016979565-804372636/Stainless_Steel_water_bottle_thermos_flask_kettle_coffee_pot_making_hydroforming_machine_water_bulging_machine.html?spm=a2700.shop_plgr.41413.39.27b76c50CMjE5V. [Accessed 19 05 2021].

[73] Alibaba, "Servo tin jar press making hydraulic pressing machine for suger canister," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/1600207207326-804372636/Servo_tin_jar_press_making_hydraulic_pressing_machine_for_suger_canister.html?spm=a2700.shop_plgr.41413.24.5bfd6c50INtd9b. [Accessed 19 05 2021].

[74] Alibaba, "High Efficiency Vacuum Flask Rim Scarp Edge Cutting Machine," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/62491670791-804372636/High_Efficiency_Vacuum_Flask_Rim_Scarp_Edge_Cutting_Machine.html?spm=a2700.shop_plgr.41413.40.63306c50vpdoD3. [Accessed 19 05 2021].

[75] Alibaba, "Sun glory Single/double wall vacuum insulated water bottle flask pot kettle Automatic pipe bottom auto welding machine," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/60790040549-804372636/Sun_glory_Single_double_wall_vacuum_insulated_water_bottle_flask_pot_kettle_Autom

atic_pipe_bottom_auto_welding_machine.html?spm=a2700.shop_plgr.41413.34.8c4d6760fcSayd. [Accessed 19 05 2021].

[76] Alibaba, "Double wall stainless steel vacuum flask machine vacuum furnace for stainless steel vacuum flask water bottle making machines," Alibaba, 2021. [Online]. Available: https://sunglorychina.en.alibaba.com/product/1600244702458-804372636/double_wall_stainless_steel_vacuum_flask_machine_vacuum_furnace_for_stainless_steel_vacuum_flask_water_bottle_making_machines.html?spm=a2700.shop_plgr.41413.9.628d36d0hoclh8. [Accessed 19 05 2021].

[77] Aztec Mouldings, "Injection Moulding Guide," Aztec Mouldings, [Online]. Available: https://www.avplastics.co.uk/injection-moulding-guide. [Accessed 19 05 2021].

[78] "Solar Home System," 24 February 2021. [Online]. Available: https://energypedia.info/wiki/Solar_Home_Systems_(SHS). [Accessed 2 May 2021].

[79] E. F. Access, "Fundamentals of Off-Grid Electrification," 4 March 2021. [Online]. Available: https://storage.googleapis.com/e4a-website-assets/Efficiency-for-Access-Design-Challenge-2020-21-Webinar-Fundamentals-Off-grid-Sector.pdf. [Accessed 4 March 2021].

[80] WHO, "Boil Water," 15 February 2011. [Online]. Available: https://www.who.int/water_sanitation_health/dwq/Boiling_water_01_15.pdf. [Accessed 12 March 2021].

[81] M. Leupold, "Through-hole versus SMD," 22 August 2017. [Online]. Available: https://www.vishay.com/docs/45242/throughholevssmdcomponents.pdf. [Accessed 9 May 2021].

[82] Wikipedia, "Heating Element," 17 April 2021. [Online]. Available: https://en.wikipedia.org/wiki/Heating_element. [Accessed 1 May 2021].

[83] Fractory, "Stainless Steels AISI 304 vs 316," 15 January 2019. [Online]. Available: https://fractory.com/stainless-steels-aisi-304-vs-aisi-316/. [Accessed 12 May 2021].

[84] K. Circuit, "Printed Circuit Board Assembly," 2021. [Online]. Available: http://www.smt-pcbassembly.com/pcb-13380617-fr4-6-layer-pcb-manufacturer-1-6mm-1oz-printed-circuit-board-assembly.html. [Accessed 10 May 2021].

[85] P. Cart, "PCB Cart," 01 January 2021. [Online]. Available: https://www.pcbcart.com/article/content/Xray-inspection-in-PCB-assembly.html. [Accessed 20 May 2021].

[86] Eurocircuits, "Tolerances on Printed Circuit Boards," 10 January 2021. [Online]. Available: https://www.eurocircuits.com/tolerances-on-a-pcb/. [Accessed 3 May 2021].

[87] SMTnet, "PCB Manufacturing Companies in Kenya," 01 January 2021. [Online]. Available: https://smtnet.com/company/index.cfm?fuseaction=browse_companies&country=116. [Accessed 10 May 2021].

[88] B. o. I. Standards, "SAFETY OF HOUSEHOLD AND SIMILAR ELECTRICAL APPLIANCES," December 2009. [Online]. Available: https://law.resource.org/pub/in/bis/S05/is.302.2.15.2009.pdf. [Accessed 15 May 2021].

[89] EPA, "Cleaming up Electronic Waste," 04 January 2021. [Online]. Available: https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste. [Accessed 12 May 2021].

[90] K. Grant, F. Goldizen, P. Sly, M.-N. Brune, M. Neira, M. Berg and R. Norman, "Health consequences of exposure to e-waste," vol. 1, pp. 350-361, 2013.

[91] R. G. J. Horne, "A literature review on the environmental and health impacts of waste," Melbourne, Australia, 2006.

[92] H. Hu, “Human health and heavy metals exposure. In Life Support: The Environment and Human Health,” MIT Press, Cambridge, UK, 2002.

[93] ST, “Complementary power Darlington transistors,” [Online]. Available: https://docs.rs-online.com/e0fd/0900766b814c8c8e.pdf. [Accessed 15 May 2021].

[94] Statista, “Warehouse Rent In Kenya,” 2021. [Online]. Available: https://www.statista.com/statistics/937523/warehouse-rent-per-sf-kenya/. [Accessed 23 4 2021].

[95] Copia, “What we do,” Copia, [Online]. Available: https://copiaglobal.com/corporate/. [Accessed 15 04 2021].

[96] Polymax, “Rubber Silicone O-Rings,” Polymax, 2021. [Online]. Available: https://www.polymax.co.uk/o-rings/rubber-silicone-o-rings/. [Accessed 16 May 2021].

[97] Shanghai ShenQi Engineering Plastics, “filled polypropylene pp flame retardant v0 recycled pp pellets,” Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/filled-polypropylene-pp-flame-retardant-v0_1600060016390.html. [Accessed 16 May 2021].

[98] Shanghai Bolting Cloth Manufacturers, “47T 120Mesh Monofilament Polyester Screen Printing Mesh,” Alibaba, 2021. [Online]. Available: https://www.ebay.co.uk/itm/123038264363?chn=ps&var=423470552258&norover=1&mkevt=1&mkrid=710-134428-41853-0&mkcid=2&itemid=423470552258_123038264363&targetid=1140014333742&device=c&mktype=pla&googleloc=9041106&poi=&campaignid=12126077997&mkgroupid=11638001. [Accessed 16 May 2021].

[99] ebay, “Select Thick 0.03mm - 0.3mm 304 Stainless Steel Fine Plate Sheet Foil 300 600mm,” ebay, 2021. [Online]. Available: https://www.ebay.co.uk/itm/123038264363?chn=ps&var=423470552258&norover=1&mkevt=1&mkrid=710-134428-41853-0&mkcid=2&itemid=423470552258_123038264363&targetid=1140014333742&device=c&mktype=pla&googleloc=9041106&poi=&campaignid=12126077997&mkgroupid=11638001. [Accessed 16 May 2021].

[100] MeshDirect, “Woven Stainless Wire Cloth 30 mesh - 0.57 mm aperture,” MeshDirect, 2021. [Online]. Available: https://www.meshdirect.co.uk/woven-stainless-wire-cloth-30-mesh-0.57-mm-aperture.html. [Accessed 16 May 2021].

[101] Zhengzhou Zhongchuang Water Purification Materials, “coconut shell activated carbon for gold recovery 8x30 mesh activated carbon,” Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/coconut-shell-activated-carbon-for-gold_62412161417.html?spm=a2700.7724857.normal_offer.d_title.3be91bcacnisdT&s=p. [Accessed 16 May 2021].

[102] Shangdong Orvey New Material Technology, “Best Price Good Quality 3-5mm Desiccant Activated Alumina Ball Desiccant for Dehydration Moisture Removal,” Alibaba, 2021. [Online]. Available: https://www.alibaba.com/product-detail/Best-Price-Good-Quality-3-5mm_1600165456782.html?spm=a2700.7724857.normal_offer.d_title.25647441zcy6o4. [Accessed 16 May 2021].

[103] Eurocircuits, “PCB Configurator,” 2021. [Online]. Available: https://be.eurocircuits.com/shop/assembly/configurator.aspx?sessionid=d67f266e-9519-4fb0-b086-5f2a29e7fbb66. [Accessed 10 May 2021].

[104] R. Headers, “PCB Headers,” 2021. [Online]. Available: https://uk.rs-online.com/web/c/connectors/pcb-connectors-wire-housings/pcb-headers/?searchTerm=single%20in%20line%20pins. [Accessed 12 May 2021].

[105] A. H. Pins, “Header Pins,” 2021. [Online]. Available: https://www.aliexpress.com/item/32790765734.html?spm=a2g0o.productlist.0.0.31aa7baaAgnfzy&algo_pvid=edf768f3-ab50-456a-b47a-46861bd0b115&algo_expid=edf768f3-ab50-456a-b47a-

46861bd0b115-25&btsid=0bb0623316212578405341518ed223&ws_ab_test=searchweb0_0,search. [Accessed 10 May 2021].

[106] R. 7805, "RS 7805," 2021. [Online]. Available: https://uk.rs-online.com/web/p/voltage-regulators/1631069/. [Accessed 12 May 2021].

[107] A. 7805, "Aliexpress 7805," 2021. [Online]. Available: https://www.aliexpress.com/item/4000191608853.html?spm=a2g0o.productlist.0.0.595d4918wbX1KW&algo_pvid=null&algo_expid=null&btsid=0b0a5565162125738170114448e41dc&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

[108] R. Fuse, "RS Fuse," 2021. [Online]. Available: https://uk.rs-online.com/web/p/cartridge-fuses/8781968/. [Accessed 10 May 2021].

[109] A. Fuse, "Aliexpress Fuse," 2021. [Online]. Available: https://www.aliexpress.com/item/1005001896278331.html?spm=a2g0o.productlist.0.0.793740feipFa0x&algo_pvid=null&algo_expid=null&btsid=0bb0623d16212572030651215eb218&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

[110] R. Inductor, "RS Components Inducors," 2021. [Online]. Available: https://uk.rs-online.com/web/p/leaded-inductors/9206985/. [Accessed 10 May 2021].

[111] A. Inductor, "Aliexpress Inductor," 2021. [Online]. Available: https://www.aliexpress.com/item/1005001424382162.html?spm=a2g0o.productlist.0.0.46ad7619IjKgpt&algo_pvid=null&algo_expid=null&btsid=0b0a555916212570008791550e780e&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

[112] R. Resistors, "RS Resistors," 2021. [Online]. Available: https://uk.rs-online.com/web/p/through-hole-fixed-resistors/7078300/. [Accessed 10 May 2021].

[113] A. Resistors, "Aliexpress Resistors," 2021. [Online]. Available: https://www.aliexpress.com/item/32979849787.html?spm=a2g0o.productlist.0.0.1bbe6c39vA7wea&algo_pvid=null&algo_expid=null&btsid=0bb0623616212566453227679e4535&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

[114] R. Capacitors, "RS Capacitors," 2021. [Online]. Available: https://uk.rs-online.com/web/p/aluminium-capacitors/9206705/. [Accessed 11 May 2021].

[115] A. Capacitors, "Aliexpress Capacitors," 2021. [Online]. Available: https://www.aliexpress.com/item/1005001973994945.html?spm=a2g0o.productlist.0.0.22a92b9auFhC6K&algo_pvid=null&algo_expid=null&btsid=0b0a555f16212563886451387e128a&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

[116] R. diode, "RS diode," 2021. [Online]. Available: https://uk.rs-online.com/web/p/schottky-diodes-rectifiers/8116099/. [Accessed 10 May 2021].

[117] A. Diode, "Aliexpress Diode," 2021. [Online]. Available: https://www.aliexpress.com/item/32855215650.html?spm=a2g0o.productlist.0.0.52e6547deW3DeE&algo_pvid=1ed35e49-5748-4966-bd65-defbaac45b5e&algo_expid=1ed35e49-5748-4966-bd65-defbaac45b5e-1&btsid=0b0a555c16212562574225344e23ed&ws_ab_test=searchweb0_0,searchw. [Accessed 10 May 2021].

[118] R. thermistor, "RS thermistor," 2021. [Online]. Available: https://uk.rs-online.com/web/p/thermistor-ics/1793901/. [Accessed 10 May 2021].

[119] A. Thermistor, "Aliexpress Thermistor," 2021. [Online]. Available: https://www.aliexpress.com/item/32375261672.html?spm=a2g0o.productlist.0.0.477a5b5a9u7nbA&algo_pvid=null&algo_expid=null&btsid=0b0a556016212553955998462eca4a&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

[120] R. Microcontroller, "RS Microcontroller," 2021. [Online]. Available: https://uk.rs-online.com/web/p/microcontrollers/1331672/?cm_mmc=UK-PPC-DS3A-_-google-_-3_UK_EN_Semiconductors_Microcontrollers_Exact-_-Microchip+-+1331672+-+ATTINY85-

20PU-_-attiny85+20pu&matchtype=e&kwd-298130547318&s_kwcid=AL!7457!3!512536241708!e!!g!!at. [Accessed 10 May 2021].

[121] R. Tip122, "RS TIP122," 2021. [Online]. Available: https://uk.rs-online.com/web/c/semiconductors/discrete-semiconductors/darlington-pairs/?searchTerm=tip122&redirect-relevancy-data=7365617263685F636173636164655F6F726465723D31267365617263685F696E746572666163655F6E616D653D4931384E53656172636847656E657269632. [Accessed 10 May 2021].

[122] A. tip122, "Aliexpress tip122," 2021. [Online]. Available: https://www.aliexpress.com/item/32556309562.html?spm=a2g0o.productlist.0.0.1ad7312eliKhEf&algo_pvid=0aa17a4f-cb79-457c-87ae-c795bea44374&algo_expid=0aa17a4f-cb79-457c-87ae-c795bea44374-4&btsid=0bb0622c16212551630768934eeaf3&ws_ab_test=searchweb0_0,searchw. [Accessed 10 May 2021].

[123] R. Thermostat, "RS Thermostat," 2021. [Online]. Available: https://uk.rs-online.com/web/p/thermostatic-switches/0339314A/. [Accessed 10 May 2021].

[124] A. Thermostat, "Aliexpress Thermostat," 2021. [Online]. Available: https://www.aliexpress.com/item/32957074669.html?spm=a2g0o.productlist.0.0.7162f70b7sJi9r&algo_pvid=null&algo_expid=null&btsid=0bb0624416212580953002385ef812&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_. [Accessed 10 May 2021].

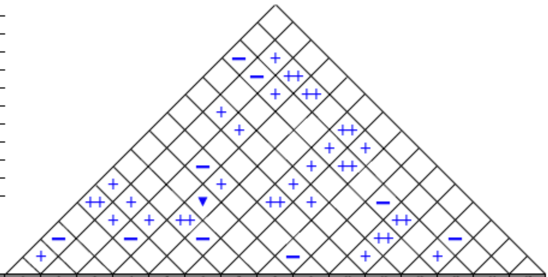
[125] M. i. China, "Heating Element," 2021. [Online]. Available: https://www.made-in-china.com/showroom/gdlees/product-detailioamRInxFOYG/China-Electric-Coffee-Kettle-Heating-Element-Electric-Heating-Plate-Heater-Tube-Tubular-Heater-Part.html. [Accessed 10 May 2021].

[126] C. Everist, L. Evason, N. Wan and L. Peacock, "Voice of Customer Presentation," University of Bath, Bath, 2021.

8 Appendix

A House of Quality

Title: ____________________
Author: ____________________
Date: ____________________
Notes: ____________________

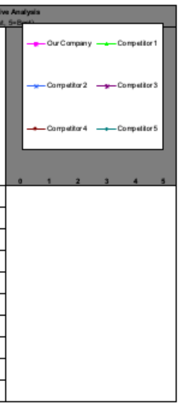


Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column # / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	1 Weight	2 Cost of production	3 User safety	4 Energy efficiency	5 Water capacity	6 Build quality	7 Environmental impact	8 Noise	9 Useful power output	10 Expected lifetime	11 Water quality	12 Serviceability	13 Maintainability	14 Heat retention	15	Our Company	Competitor 1	Competitor 2	Competitor 3	Competitor 4	Competitor 5
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▲	▲	x	x	▲	▼	▲	▲	▲	▲	▲	▲							
1	9	14.7	5.0	Boils water reliably		▲	Θ	▲		O				▲	Θ	Θ	O								
2	9	11.8	4.0	Easy to use	O		O		O					O		Θ	O	▲							
3	9	14.7	5.0	Energy efficient		O		Θ	▲	O	O	Θ	Θ			▲	▲	Θ							
4	9	8.8	3.0	Allows for multasking	O		Θ		O																
5	9	8.8	3.0	Cheap to buy	Θ	Θ	O		O	Θ	O			O	▲		▲	O							
6	9	11.8	4.0	Boil a useful amount of water	Θ	O		O	Θ							▲		▲							
7	9	5.9	2.0	Should be quick to boil		O	O	Θ	Θ	▲			Θ					Θ							
8	9	2.9	1.0	Compact size	Θ	Θ	▲	O	Θ	▲	O					Θ	▲	Θ							
9	9	11.8	4.0	Long life cycle		▲		O		Θ			O	Θ		O	Θ								
10	9	8.8	3.0	Robust	▲	O	O			Θ	O			Θ		▲	▲	▲							

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target or Limit Value	< 5 kg	< £50	N/A	~ 60%	1.5L	N/A	N/A	< 70dBA	300W	10,000 cycles	N/A	N/A	N/A	N/A	
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)					5			1	7	3					
Max Relationship Value in Column	9	9	9	9	9	9	3	9	9	9	9	9	9	9	
Weight / Importance	282.4	255.9	320.6	279.4	288.2	361.8	105.9	132.4	220.6	261.8	141.2	335.3	220.6	270.6	
Relative Weight	8.1	7.4	9.2	8.0	8.3	10.4	3.0	3.8	6.3	7.5	4.1	9.6	6.3	7.8	

Competitive Analysis
(0=Worst, 5=Best)



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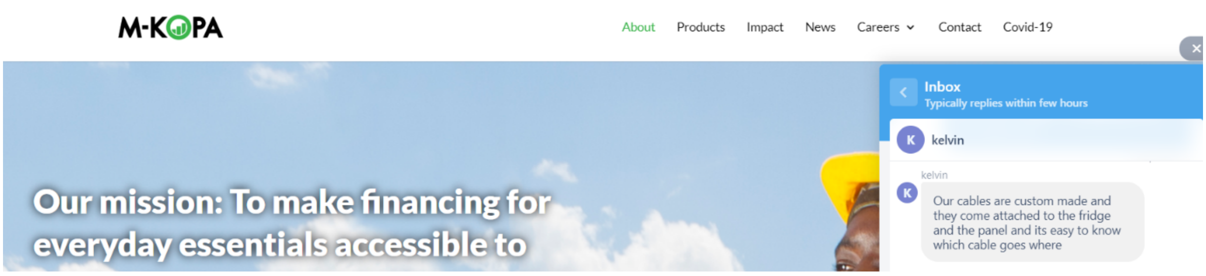
B DFMEA

Process	Component	Function	Potential Failure Mode	Potential Effect of Failure	Potential Cause of Failure	Existing Conditions					Recommended Action	Action Results				
						Current Controls	Occurrence (O)	Severity (S)	Detectability (D)	RPN = O x S x D		New Controls	Occurrence (O)	Severity (S)	Detectability (D)	RPN = O x S x D
Manufacture	Vacuum Casing	Heat Retention	Vacuum not formed correctly	Reduced efficiency	Incorrrect manufcature	QA Check	3	3	4	36	Perform visual inspection of PCB	Additional checks	3	3	3	27
	Circuit Board	Electronic Processing	Short Circuiting	Electrical damage to kettle	Excess solder used	QA check	3	3	3	27	Perform visual inspection of PCB	Additional checks	2	3	2	12
			Poor electrical connection	Reduced/ No function	Dry joint	QA check	3	2	3	18	Perform visual inspection of PCB	Additional checks	2	3	2	12
Assembly	Operation Switches	Initiating heating	Maloperation	Incorrect operation mode selected	Heat and boil switches connected to the incorrect microcontroller pin	QA check	3	3	4	36	Use coloured wires to differentiate	Poka-yoke	2	3	2	12
	Circuit Board	Electronic Processing	Components being dislodged	Reduced/ No function	PCB incorrectly mounted	QA check	2	3	3	18	Rattle check	Additional checks	2	3	2	12
	Filter	Removing solid particles	Damage to filter	Reduced/ No function	Incorrectly mounted	QA check	3	4	3	36	Seated fit	Poka-yoke	2	4	2	16
Transport	Vacuum Casing	Heat Retention	Impact Damage	Visual Discrepancies	Incorrectly packaged	QA check	3	2	2	12	Tighter packaging	Stricter controls	3	2	1	6
	Plastic Casing	Filter Containment	Impact Damage	Visual Discrepancies	Incorrectly packaged	QA check	3	2	2	12	Tighter packaging	Stricter controls	3	2	1	6
			Impact Damage	Filter Damage	Incorrectly packaged	QA check	2	3	2	12	Tighter packaging	Stricter controls	2	3	1	6
Filtration	Filter	Removing solid particles	Carbon or Alumina particles leak into boiling chamber	Contaminated water	Faulty filter mesh	QA check	3	5	4	60	Perform mesh checks for every batch	Additional checks	2	5	2	20
			Filter blocked by sediment	Water remains in filter system	Filter mesh too fine	Component test	2	3	1	6	Confirm filter time	Additional testing	2	3	1	6
					Excessive use	Lifecycle test	3	3	1	9	Confirm filter lifetime	Additional checks	2	3	1	6
Heating	Heating Element	Heating water	Scale forms on heating plate	Reduced heating efficiency	Hard water	Heating plate testing	3	2	2	12	Perform water tests	Additional testing	2	2	2	8
			Water gets under base plate	Electronic damage	Tolerance error	CAD checks	3	5	3	45	Additional tolerance check	Tolerance check	2	5	3	30
					Manufacturing error	QA check	3	5	3	45	Stricter controls	QA check	2	5	3	30
	Vacuum Casing	Heat Retention	Outer casing becomes hot	Harm to user and reduced efficiency	Vacuum seal is broken	QA check	3	4	5	60	Stricter controls	Additional checks	2	4	4	32
					Inner and outer layers contact due to mismanufacture	QA check	2	4	4	32	Stricter controls	Additional checks	2	4	3	24
	Plastic Casing	Filter Containment	Plastic degrades or melts	Harm to user and product failure	Low thermal resisatnce of plastic	Material Testing	2	5	5	50	Reperform plastic tests to confirm suitability	Additional checks	2	5	3	30

C Discussion with MKOPA



D Filter Costs Table

Part Number	Component	Material	Units	Cost (£)
UOBG6_PART_0001	Cartridge Body	Polypropylene	1	0.053672
UOBG6_PART_0002	Cartridge Bottom Snap	Polypropylene	1	0.008711
UOBG6_PART_0003	Lid Bottom Snap	Polypropylene	1	0.009078
UOBG6_PART_0004	Lid Top	Polypropylene	1	0.007532
		Total for 1 cartridge		**0.078993**
UOBG6_PART_0005	Polyester mesh	Polyester	2	0.006758
UOBG6_PART_0006	Stainless steel mesh	Stainless Steel 304	2	0.162338
UOBG6_PART_0007	Stainless Steel sheet circle	Stainless Steel 304	4	0.468621
		Total for 1 mesh disc		**1.106337**
UOBG6_PART_0008	Cartridge O-ring Seal	Silicone rubber O-rings	1	0.3 [96]
UOBG6_PART_0009	Lid O-ring Seal	Silicone rubber O-rings	1	0.25
NA	Activated Carbon 100g	Activated Carbon	1	0.057378
NA	Activated Alumina 50g	Activated Alumina	1	0.030065
		Total Filtrate in 1 cartridge		**0.087443**
		Total Assembled Cartridge		**2.841667**
		Total Including Filtrate		**2.929111**

Raw Material Prices		Reference
Polypropylene £/Kg	2.16	[97]
Polyester £/1.65x50m^2	75.5	[98]
Stainless Steel Sheet 304 £/0.3x5m^2	81.54	[99]
Stainless Steel 304 30Mesh £/1.22x1m^2	25	[100]
AC £/Kg	0.61485	[101]
AA £/Kg	0.5034	[102]

E Circuit Cost Breakdown

Component	Quantity	Prototype Cost	Production Cost	Source
Circuit Board	1	£15	£1.50	[103] [84]
Single-In-Line Connectors 2 Pin	4	£1.28	£0.80	[104] [105]
Single-In-Line Connectors 3 Pin	1	£0.48	£0.20	[104] [105]
Voltage Regulator 7805	1	£0.60	£0.08	[106] [107]
Fuse	1	£0.96	£0.06	[108] [109]
Inductor ELC09D	1	£0.23	£0.15	[110] [111]
Resistor	10	£0.10	£0.05	[112] [113]
470µF Capacitor	2	£0.17	£0.05	[114] [115]
1000µF Capacitor	1	£0.17	£0.05	[114] [115]
Diode 1N5400	2	£0.40	£0.18	[116] [117]
SPST Momentary Switch	1	£0.28	£0.28	[61]
SPDT Rocker Switch	1	£0.07	£0.07	[62]
NTC Thermistor	1	£1.40	£0.17	[118] [119]
Microcontroller ATTINY85-20PU	1	£1.06	£1.06	[120]
Transistor TIP122	1	£0.43	£0.12	[121] [122]
Breaker Switch	1	£5.11	£0.40	[123] [124]
Heating Element	1	£1.50	£1.50	[125]
Total	31	£29.00	£7.00	

F Microcontroller Datasheet

Atmel

Atmel 8-bit AVR Microcontroller with 2/4/8K Bytes In-System Programmable Flash

ATtiny25/V / ATtiny45/V / ATtiny85/V Summary

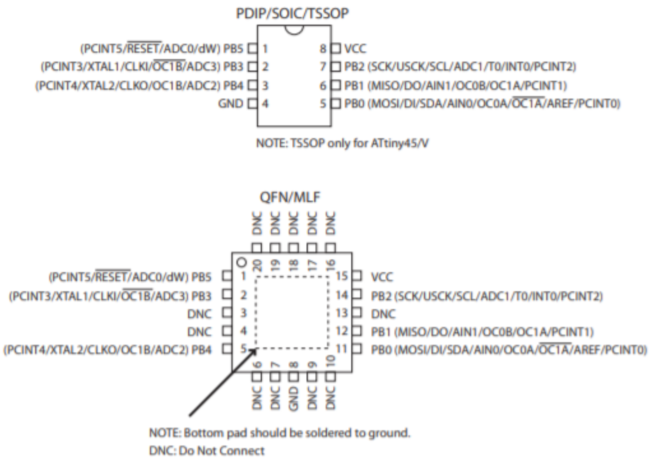
Features

- High Performance, Low Power AVR® 8-Bit Microcontroller
- Advanced RISC Architecture
  - 120 Powerful Instructions – Most Single Clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
- Non-volatile Program and Data Memories
  - 2/4/8K Bytes of In-System Programmable Program Memory Flash
    - Endurance: 10,000 Write/Erase Cycles
  - 128/256/512 Bytes In-System Programmable EEPROM
    - Endurance: 100,000 Write/Erase Cycles
  - 128/256/512 Bytes Internal SRAM
  - Programming Lock for Self-Programming Flash Program and EEPROM Data Security
- Peripheral Features
  - 8-bit Timer/Counter with Prescaler and Two PWM Channels
  - 8-bit High Speed Timer/Counter with Separate Prescaler
    - 2 High Frequency PWM Outputs with Separate Output Compare Registers
    - Programmable Dead Time Generator
  - USI – Universal Serial Interface with Start Condition Detector
  - 10-bit ADC
    - 4 Single Ended Channels
    - 2 Differential ADC Channel Pairs with Programmable Gain (1x, 20x)
    - Temperature Measurement
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
- Special Microcontroller Features
  - debugWIRE On-chip Debug System
  - In-System Programmable via SPI Port
  - External and Internal Interrupt Sources
  - Low Power Idle, ADC Noise Reduction, and Power-down Modes
  - Enhanced Power-on Reset Circuit
  - Programmable Brown-out Detection Circuit
  - Internal Calibrated Oscillator
- I/O and Packages
  - Six Programmable I/O Lines
  - 8-pin PDIP, 8-pin SOIC, 20-pad QFN/MLF, and 8-pin TSSOP (only ATtiny45/V)
- Operating Voltage
  - 1.8 - 5.5V for ATtiny25V/45V/85V
  - 2.7 - 5.5V for ATtiny25/45/85
- Speed Grade
  - ATtiny25V/45V/85V: 0 – 4 MHz @ 1.8 - 5.5V, 0 - 10 MHz @ 2.7 - 5.5V
  - ATtiny25/45/85: 0 – 10 MHz @ 2.7 - 5.5V, 0 - 20 MHz @ 4.5 - 5.5V
- Industrial Temperature Range
- Low Power Consumption
  - Active Mode:
    - 1 MHz, 1.8V: 300 µA
  - Power-down Mode:
    - 0.1 µA at 1.8V

Rev. 2586QS–AVR–08/2013

1. Pin Configurations

Figure 1-1. Pinout ATtiny25/45/85



1.1 Pin Descriptions

1.1.1 VCC

Supply voltage.

1.1.2 GND

Ground.

1.1.3 Port B (PB5:PB0)

Port B is a 6-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port B output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port B pins that are externally pulled low will source current if the pull-up resistors are activated. The Port B pins are tri-stated when a reset condition becomes active, even if the clock is not running.

G Circuit DFMEA

Process	Component	Potential Failure Mode	Potential Effect of Failure	Potential Cause of Failure	Existing Conditions					Action Results				
					Current Controls	Occurrence (O)	Severity (S)	Detectability (D)	RPN = O x S x D	New Controls	Occurrence (O)	Severity (S)	Detectability (D)	RPN = O x S x D
Manufacture	Circuit Board	Short Circuiting	Electrical damage to kettle	Excess solder used	QA check at manufacturer	3	3	3	27	Additional checks on assembly	2	3	2	12
		Poor electrical connection	Reduced/ No function	Dry joint	QA check at manufacturer	3	2	3	18	Additional checks on assembly	2	3	2	12
		Components being dislodged	Reduced/ No function	Incorrect assembly	QA check at manufacturer	3	3	2	18	Additional checks on assembly	2	3	2	12
Assembly	Circuit Board	PCB does not fit	Wasted materials	Drilling tolerance too large	QA check at manufacturer	2	2	2	8	Jig check at manufacturer	1	2	2	4
				Mounting holes drilled incorrectly	QA check at manufacturer	3	2	2	12	Jig check at manufacturer	2	2	2	8
		Components being dislodged	Reduced/ No function	PCB incorrectly mounted	QA check	2	3	3	18	Additional checks on assembly	2	3	2	12
	Wires	Peripheral components not connected	Reduced/ No function	Incorectly assembled	QA check	3	2	2	12	Additional checks on assembly	3	2	1	6
				Single-in-line wires come out	QA check	2	3	2	12	Electrical test	2	3	1	6
		Damage	Reduced/ No function	Wires cut on sharp edges	QA check	2	3	3	18	Ensure there are no sharp edges	2	3	2	12
Operation	Heating Element	Impact Damage	Reduced/ No function Fire risk Reduced heating efficiency	User maloperation	Heating plate testing	3	4	2	24	Additional testing	2	4	2	16
	Circuit Board	Impact Damage	Electronic damage	User maloperation	PCB impact testing	3	4	3	36	Additional testing	2	4	3	24