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1 Introduction

In this report, systems engineering techniques will be defined and used to break down and improve upon a regular household item. Each systems engineering tool will be explained in section 2, with a worked example shown in section 3, culminating in a design book of systems engineering tools (found in Appendix 1) that details the entire system behind the chosen household item.

1.1 Use Case

The use case for the assignment will be based around improving the design of the kettle. The desire is to outline the functions and requirements of a kettle that is easier to use, easier to clean and more resistant to limescale buildup due to the customers being based in an area with hard water.

2 Systems Engineering Overview

A system is an assembly of elements such as components, people, software, data and more, which combine to form a function or achieve a purpose. An example of a system is an aircraft. An aircraft consists of engines, flight control surfaces (such as wings, flaps, and tail), trained pilots, maintenance regimes, and air traffic control. If any of these elements fail to function, then the system itself may not be capable of achieving the desired output, or it may not be able to operate safely.

Systems engineering is a series of tools utilised to design a system from the ground up. It analyses the whole system throughout its life cycle and is driven by the system requirements.

2.1 Key Customer Requirements

A requirement is a needed, or desired, expectation from the customer. It defines the basis of the design and is what must be met for the system to effectively achieve its function. To design the system, stakeholders need to be identified and their requirements laid out. These can be collated through personal

communications, meetings, brainstorming, emails and essentially any form of communication. At this point, no specific tool is required for gathering requirements, but systems engineering software tools may help with the organisation of information, such as IBM Doors or Polarion (Figure 1).

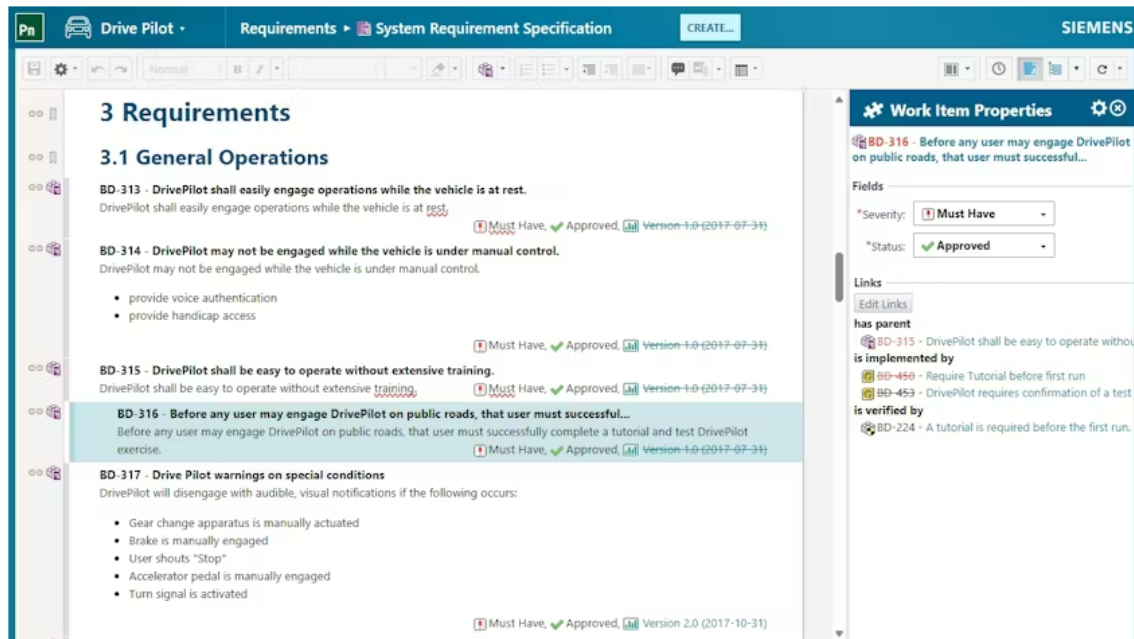


Figure 1 - Image taken of the Polarion systems engineering software [1].

2.1.1 Pairwise Analysis

After the customer requirements have been established, it is important to understand which requirements are more important than others. One tool that can be utilised for doing this is a pairwise analysis. For a pairwise analysis, each requirement is compared with every other requirement and is ranked either 0, 1, 5 or 9. If 0, then there is no preference between the two requirements; 1 is a slight preference, 5 is a preference, and 9 is a strong preference. After ranking the scores for each requirement are multiplied together, and a ratio between the final score and the sum of all scores determines a ranking of all the requirements, as shown in Figure 2.

2.1.2 MoSCoW Method

Other requirement prioritisation tools exist, such as the “MoSCoW method”, which is good for filtering through requirements by assigning them to 4 different

categories: must have, should have, could have and won't have. Whilst less precise than a numerical comparison, it is a simple and fast method of requirement filtering.

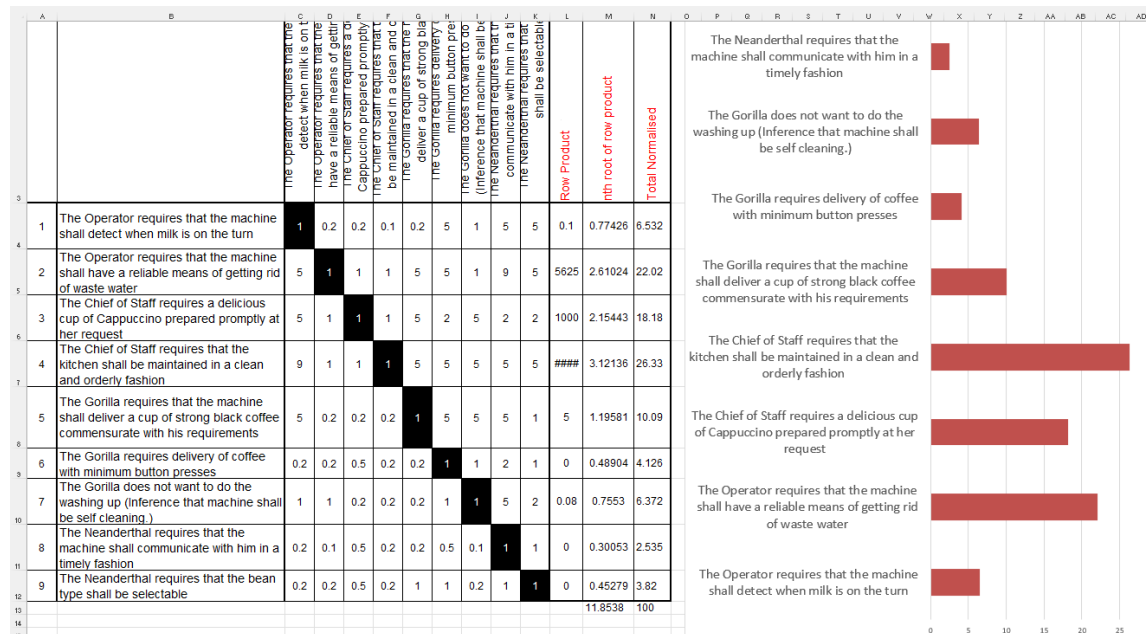


Figure 2 – Complete pairwise analysis as taken from Holley's example design book [2].

2.2 Critical System Functionality, Concept Derivation and Design Choices

Critical System Functionality is a list of functions that the system must perform correctly in order to meet the stakeholders' requirements. Failure to perform these requirements means the system is no longer acceptable. A function is an action or process that the system performs to achieve a specific outcome which will contribute to achieving the key customer requirements.

Through breaking down the system into functions and requirements new concepts can be derived for the system taking inspiration from similar systems before or combining multiple different systems into one integrated system.

2.2.1 Quality Function Development Matrix

Functions are identified through design meetings and literature reviews, taking ideas from previous systems, or systems with similar functions. Some functions

are taken from the use case; others will be established after a functional analysis of the system has been performed. The outlined functions then have to be analysed so that the critical design functions can be established. This is done through use of a Quality Function Development Matrix (QFD) as shown in figure 3. A QFD creates a link between customer requirements and system functionality [3].

The result upon completion of the QFD is a list of system functions and how important they are in comparison to the other functions. The higher the score the more important the function.

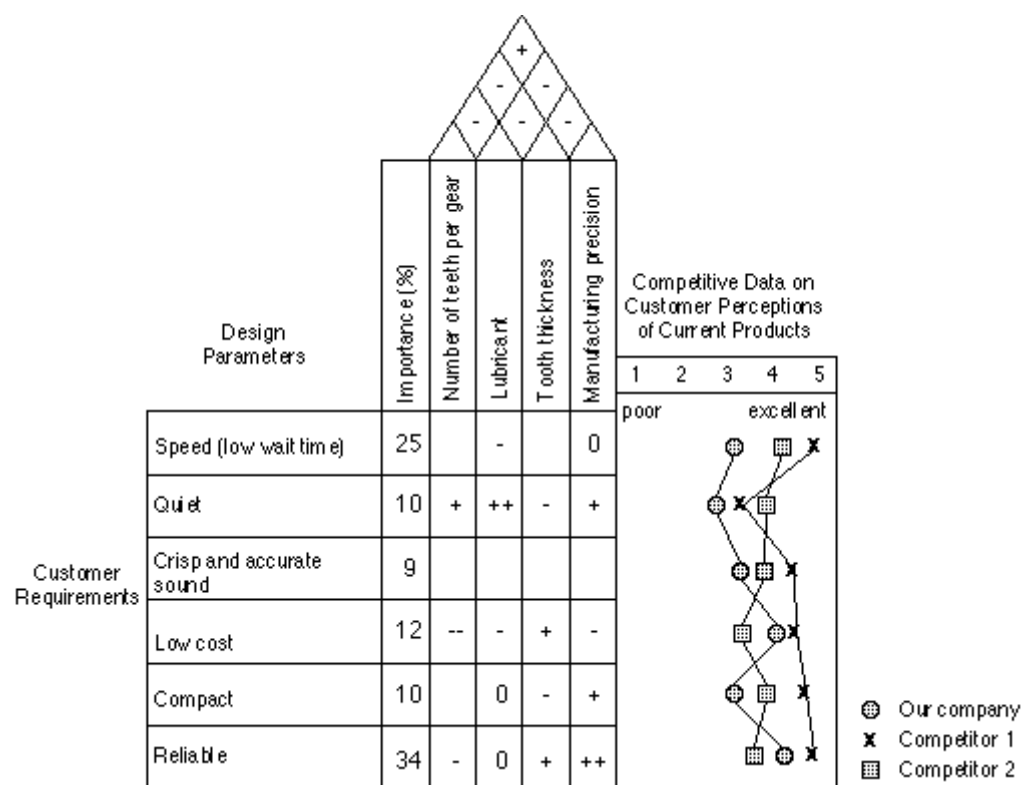


Figure 3 - An example Quality Function Development Matrix [4].

2.2.2 Functions Means Analysis

A functional means analysis (FMA) is a tool that is used to identify how a system's function can be achieved. For example, a pilot needs to know information regarding the planes current state in the air, such as plane attitude, current flying altitude and airspeed. With the function being to measure the airspeed of the aircraft, the means is through use of several pitot tubes.

Functions and means are typically charted out in a table, and if a design is being improved upon, then the table may also include a comparison of how a function used to be carried out, compared to how it would be carried out in the new design.

FUNCTION – MEANS ANALYSIS CHART													
System: Intelligent Dish Washer		Sub-System		Date: 1 April		Author: S Clean		Issue: 1.0		Reviewed: D. Dirt			
FUNCTION		MEANS											
Detect Load Make Up	Bar coded Items	Vision recognition	Infra red camera and recognition	Ultrasound	Electronic Tags	User defined	Mass Spectroscopy	Position indicators in baskets					
Measure Water Hardness	Hardness sensor	Installation defined	User defined										
Load Dirty Items	Bottom Hinge Door	Slide door Hinge	Top Door	2 Sliding Baskets	Conveyor								
Unload Cleaned Items	Bottom Hinge Door	Slide door Hinge	Top Door	2 Sliding Baskets	Conveyor								
Load Cleaning Agents	Pull out tray	In-door compartment	In-door Hopper	In machine body Hopper	No cleaning agents								
Fill Water	Gravity feed	Main Water pressure	Reciprocating Pump	Rotary Pump	Centrifugal Pump								
Drain Water	Gravity feed	Vaporisation	Reciprocating Pump	Rotary Pump	Centrifugal Pump	Clean and recycle water							
Heat Water	Electric Element	Gas Burner	House hot supply and mix with cold	Solar									
Wash	Rotating Spray arm – one off	Rotating Spray arm – two off	Wall mounted jets	Emersion	Water bath								
Rinse	Rotating Spray arm – one off	Rotating Spray arm – two off	Wall Mounted jets	Emersion	Water bath								
Dry Contents	Electric Element	Gas burner	Blow dry	Left wet	Left wet and hand dry	Spin dry							
Select Cycle	Clockwork dial - user defined	Fuzzy Logic	Neural Network	Rule Based System	Deterministic equation	Look up table	Fixed one cycle						
Control Cycle	Clockwork Controller	Microprocessor and software	Signal Processor	PLC	ASIC	Analogue hardware	Digital hardware	Cams and gears					
Receive User Input	Dial	Switches/buttons	LCD touch screen	Plasma touch screen	Soft key pad	Hard key pad	Voice recognition	Mobile phone as remote	TV style remote				
Display User Messages	Dial	Switches/buttons	LCD touch screen	Plasma touch screen	Audible - loudspeaker	Mobile phone	LCD in TV style remote						
Support	Metal Sub-frame	Monocoque	Back-plane Chassis	Force field									
Protect	Steel Casing	Injection/ vacuum moulded plastic	Carbon Fibre casing	Steel side/back casing with plastic facia									
Interface to services	Standard EU/BS Fittings	Snap-fit connectors	Fully plumbed in										

Figure 4 – An example Functions Means Analysis Chart [5].

2.2.3 Pugh Matrix

The Pugh matrix is a type of comparative matrix where the leading design concepts are ranked against the customer requirements, it is a qualitative ranking of each design and helps determine which design is likely the best one for the chosen criteria [6]. A basic Pugh matrix is simple to use and create, it consists of a table with customer requirements at the start of each row, and a ranking of each design against those requirements in each column as shown in figure 5.

3 Use Case, design of an improved kettle

3.1 Key Customer Requirements and Pairwise Analysis

The key customer requirements selected for the design of an improved kettle are as shown in table 1.

Table 1 – A table showing all the key customer requirements for the selected use case.

	Key Customer Requirements
1	The operator requires that the kettle shall heat water to boiling temperature
2	The operator requires the kettle to be powered using household mains plug sockets
3	The operator requires the kettle to be capable of boiling water up to a capacity of 1.5 litres
4	The operator requires that the kettle be easy to fill and empty
5	The operator requires that the kettle filters the water, due to the hard water in the area
6	The operator requires that the kettle has a clear indicator to display when the kettle is on
7	The operator requires the kettle be resistant to limescale buildup
8	The kettle shall comply with safety regulations
9	The operator requires the kettle to be easily cleanable

Requirement 1 specifies the primary function of a kettle, to heat water up to boiling temperature. As this is to be used as a household item, the stakeholder has specified that *requirement 2* is necessary. *Requirement 8* specifies that the kettle should comply with safety regulations, the regulations that must be met is

the Electrical Equipment (Safety) Regulations 2016 as the customer is based in the United Kingdom.

Following the listing of the key customer requirements a pairwise analysis was undertaken to rationalise the requirements. The result of the pairwise analysis is shown in figure 5, the matrix for the pairwise analysis that the chart derives from can be found in appendix A.1.

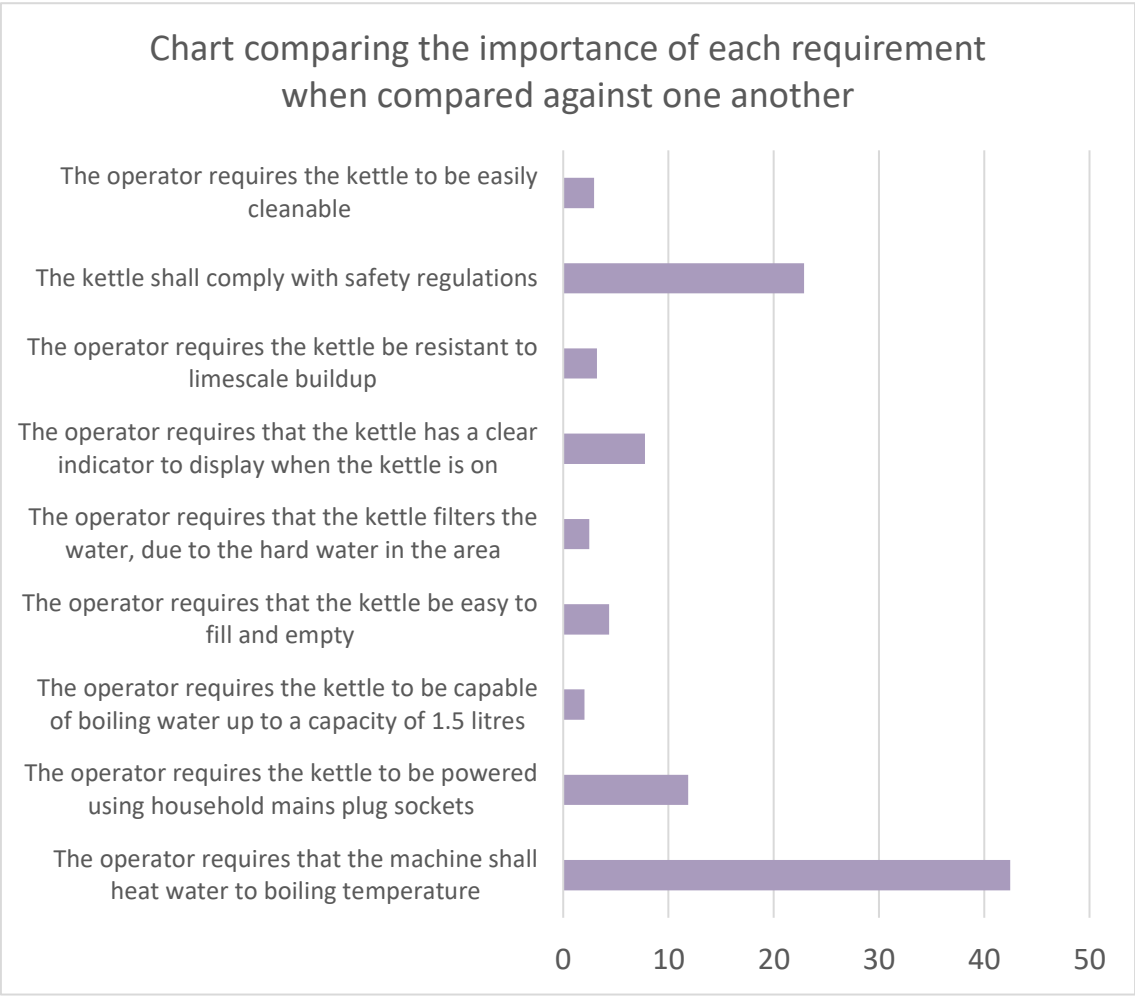


Figure 5 – A chart comparing each requirement against one another, the scoring is a rating of how important the requirement is, this was calculated using a pairwise analysis matrix.

3.2 System Functions

The various functionality of a kettle is outlined in table 2.

Table 2 - A table outlining the functions of the kettle design.

	System Functions
1	It must be able to contain water
2	It must heat the water
3	It must turn off the heating element when the water is boiling
4	It should indicate when it is heating the water
5	It should filter the water
6	It should start the heating process only when the button, or switch, is pressed.

3.3 Quality Function Development Matrix

After establishing the key requirements and functions a QFD (Appendix A.2) could be made for the kettle, putting each requirement against each function to create a graph showing the functional importance of the system (Figure 6).

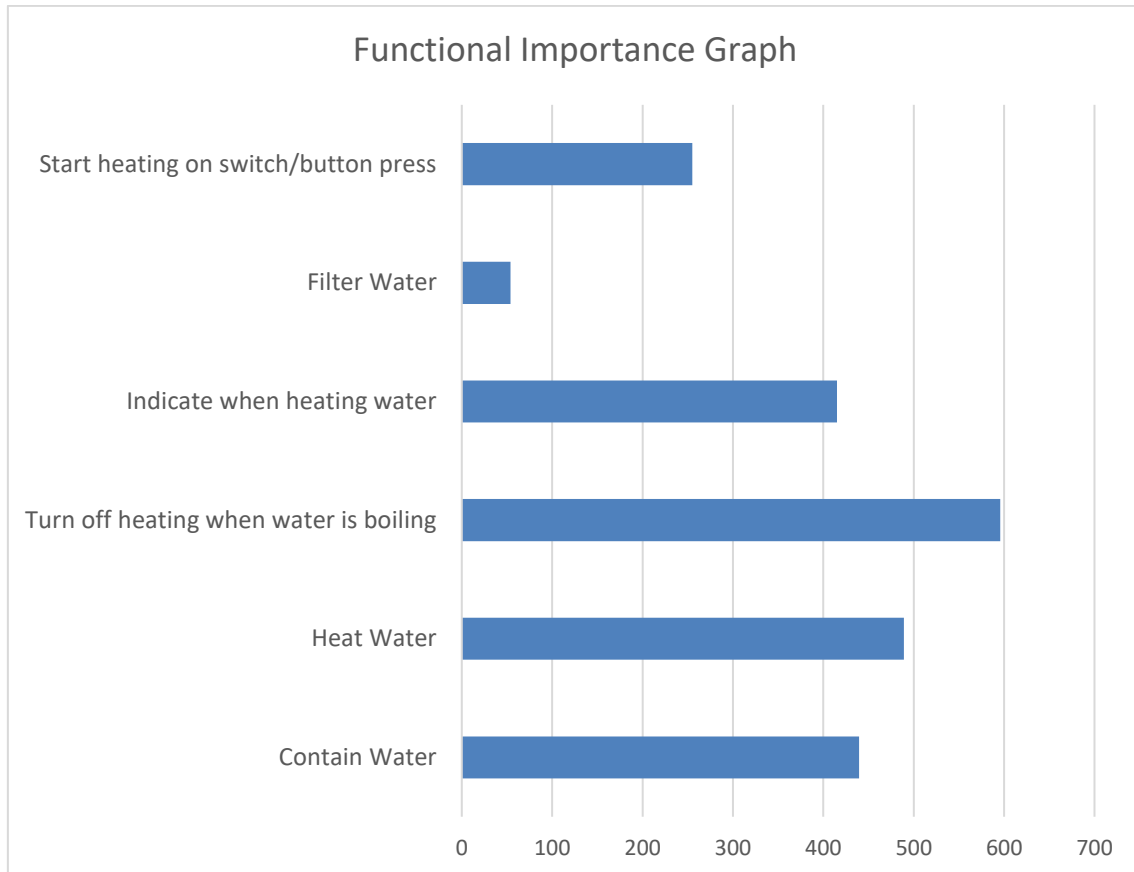


Figure 6 - A chart showing the relative importance of each function of the kettle, as compared against each requirement.

3.4 Design Concepts

The current design (Figure 7) is a simple kettle with no additional functionality; it only serves the primary function which is to heat water.



Figure 7 - An image of the current machine used by the customer [7].

The second design option (Figure 8) is a kettle with a similar capacity; however, it also includes a removable and easy to clean filter. The container itself is made of glass as opposed to plastic which is easier to clean and is less likely to get a buildup of limescale.



Figure 8 - The second design option, a glass kettle with integrated filter. [8].

The final design option (Figure 9) is a countertop water boiler; it has a much larger capacity and can heat water without the need for an operator to start the machine. It also includes a filter with a display that will check when the filter has reached the end of its lifespan and needs to be replaced.



Figure 9 - The final design option, a countertop water boiler [9].

3.5 Pugh Matrix

A Pugh matrix was used to compare each of the 3 designs against each function, this would qualitatively establish which of the design options would be best to use, the matrix is shown in figure 10.

		Relative Importance Equal	Relative importance Weighted	Current Machine	Glass kettle with Filter	Countertop Water Boiler
WHATs - Customer Requirements	How much:- From QFD 1					
The operator requires that the machine shall heat water to boiling temperature		5	42.4699518	0	0	1
The operator requires the kettle to be powered using household mains plug sockets		5	11.8626746	0	0	0
The operator requires the kettle to be capable of boiling water up to a capacity of 1.5 litres		5	2.02343003	0	0	2
The operator requires that the kettle be easy to fill and empty		5	4.35934785	0	0	-2
The operator requires that the kettle filters the water, due to the hard water in the area		5	2.48693105	0	2	2
The operator requires that the kettle has a clear indicator to display when the kettle is on		5	7.77127607	0	1	1
The operator requires the kettle be resistant to limescale buildup		5	3.21199496	0	2	1
The kettle shall comply with safety regulations		5	22.8718163	0	0	0
The operator requires the kettle to be easily cleanable		5	2.94257737	0	1	-1
Development Cost		5	10	0	0	0
Purchase Cost		5	10	0	-1	-2
Availability		5	10	0	-1	-2
				0	20	0
				0	2.111705	10.81267
Ranking		100		0	17.88829	-10.8127

Figure 10 - A complete Pugh matrix comparing each kettle design against the key customer requirements.

The Pugh matrix provides qualitative reasoning behind why in this specific scenario, the glass kettle with a filter is the most appropriate design to use going forward.

4 Summary

The tools used were effective in the development of an improved electric kettle, by effectively communicating what the key functions and requirements are and why. By qualitatively comparing each of the requirements, functions and designs it allows the engineer to provide effective evidence behind set design choices. The implementation of these tools also helps reduce the costs of development by reducing the need for prototyping.

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Appendix A Design Book

A.1 Pairwise Analysis

	1	2	3	4	5	6	7	8	9	Calc		Calc
	Pairwise comparison of requirements 1 = No Preference, Reciprocal = 1 2 = Slight Preference, Reciprocal = 0.5 5 = Preference, Reciprocal = 0.2 9 = Strong preference = 0.11											
1	The operator requires that the machine shall heat water to boiling temperature	1	9	9	9	9	9	9	9	23914845	6.604683	42.47
2	The operator requires the kettle to be powered using household mains plug sockets	0.11	1	5	2	5	5	5	5	247.5	1.844815	11.86
3	The operator requires the kettle to be capable of boiling water up to a capacity of 1.5 litres	0.11	0.2	1	0.5	0.5	0.2	0.5	0.5	3.025E-05	0.314672	2.023
4	The operator requires that the kettle be easy to fill and empty	0.11	0.5	2	1	5	0.5	0.11	2	0.03025	0.677941	4.359
5	The operator requires that the kettle filters the water, due to the hard water in the area	0.11	0.2	2	0.2	1	0.2	0.11	0.5	0.0001936	0.386753	2.487
6	The operator requires that the kettle has a clear indicator to display when the kettle is on	0.11	0.2	5	2	5	1	0.2	5	5.5	1.208544	7.771
7	The operator requires the kettle be resistant to limescale buildup	0.11	0.11	2	2	0.5	0.2	1	2	0.001936	0.499511	3.212
8	The kettle shall comply with safety regulations	0.2	5	9	9	9	5	1	5	91125	3.556893	22.87
9	The operator requires the kettle to be easily cleanable	0.11	0.2	2	0.5	2	0.2	0.2	1	0.00088	0.457613	2.943
											15.55142	100
												Total Normalised
												nth root of row product

A.2 Design QFD 1

How	Importance	Contain Water	Heat Water	Turn off heating when water is boiling	Indicate when heating water	Filter Water	Start heating on switch/button press
Requirements							
The operator requires that the machine shall heat water to boiling temperature	42.46995	9	9	9	3		3
The operator requires the kettle to be powered using household mains plug sockets	11.86267		9		1		3
The operator requires the kettle to be capable of boiling water up to a capacity of 1.5 litres	2.02343	9					
The operator requires that the kettle be easy to fill and empty	4.359348	9				3	
The operator requires that the kettle filters the water, due to the hard water in the area	2.486931					9	
The operator requires that the kettle has a clear indicator to display when the kettle is on	7.771276			1	9		3
The operator requires the kettle be resistant to limescale buildup	3.211995					3	
The kettle shall comply with safety regulations	22.87182			9	9		3
The operator requires the kettle to be easily cleanable	2.942577					3	
		440	489	596	415	54	255

A.3 Pugh Matrix

		Relative Importance Equal	Relative importance Weighted	Current Machine	Glass kettle with Filter	Countertop Water Boiler
WHATs - Customer Requirements	How much:- From QFD 1					
The operator requires that the machine shall heat water to boiling temperature		5	42.4699518	0	0	1
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Development Cost		5	10	0	0	0
Purchase Cost		5	10	0	-1	-2
Availability		5	10	0	-1	-2
				0	20	0
				0	2.111705	10.81267
Ranking		100		0	17.88829	-10.8127