



UWTSD
Level 4 Systems Engineering

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System engineering a container for hot beverages.

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Abstract

This report derives design solutions to maintain hot beverages at comfortable drinking temperatures. It uses solution neutral requirements and system engineering techniques to justify its concept selection. The resulting analysis selected the “V3” concept comprising of borosilicate glass, reinforced polymer shell, phase change material lining, aerogel insulation, self-regulating positive temperature coefficient heater, induction charging coaster, silicone grip sleeve, LED indicator ring and antimicrobial coating. The report further discusses the principles of systems engineering, QFD methodology, the limitations of the single assessor evaluation used, and the advantages and disadvantages of the tools used.

Keywords:

Systems Engineering, solution neutral, household design, functionality, design, quality function deployment

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1 Introduction

This report presents a design solution for maintaining hot beverages at comfortable drinking temperatures. A sequence of systems engineering tools are applied to derive design solutions from user needs.

1.1 Use case

The following use case was developed prior to any requirement gathering and has been revised once again after selecting the winning concept.

1.1.1 Actors

The actors are defined as follows:

- (Actor A): Consumes their hot beverage quickly, 15 minutes
- (Actor B): Leaves their beverage for extended periods, 2+ hours
- (Actor C): Consumes their beverage over 30-60 minutes with breaks between sips.

1.1.2 Pre-conditions

These actors have the following pre-conditions:

- Sufficient manual dexterity to grasp, hold, and lift a drinking vessel independently
- Have prepared a hot beverage at a temperature between 65 and 95°C
- Cognitive, coherent, and possess a basic understanding and repeat experience in consuming hot liquids safely
- Understand there is a burn risk involved
- There is sufficient budget to design, test and produce a solution
- The solution is compliant with relevant safety standards

1.1.3 Post-conditions

The post-conditions are as follows:

- The solution can maintain a beverage at the desired drinking temperature for the entire consumption period

- The solution is safe to use
- The solution does not alter the quality of the beverage
- The solution can be cleaned with minimal effort and reused

1.1.4 Basic flow

The basic flow is as follows:

- The solution must maintain a hot beverage at a comfortable temperature for the duration of the consumption period for volumes between 100ml and 350ml.

1.1.5 Operational flow

The intended operational flow is as follows:

1. User prepares hot beverage at initial temperature of at least 65°C
2. User places beverage into the solution
3. The solution begins maintaining the liquid temperature
4. As the liquid naturally cools, the solution acts to return to target range
5. The user drinks from the vessel at any point
6. Steps 3-5 are repeated
7. When the volume of liquid drops below 50ml, or the user finishes their drink, the solution returns to a passive state.

The actors will experience the following:

- Actor A will finish their beverage before significant cooling occurs and may not require a cycle.
- Actor B will leave their drink for multiple hours and will require multiple cycles
- Actor C will require between 1 and 2 cycles.

1.1.6 Alternative flow

The alternative flow is as follows:

- Incorrect substances: The solution may encounter a non-beverage liquid. It must either detect the incompatibility or heat it safely without creating a hazard.
- Refilling: The user may refill their beverage with fresh hot liquid. If so, the solution must accommodate for the new volume and temperature without a malfunction.
- External surface contact: The solution may have a surface above safe handling temperature. The solution must maintain a temperature that does not harm the users in contact with it.
- Leaving liquid unattended: The solution must not be a hazard if left unattended
- Power loss: The solution must not create a hazard if it loses energy.
- Impact: If the vessel is dropped during use, the design must minimise the risk of breakage.

1.1.7 Revisions based on winning concept

The following revisions have been made after performing the DFMEA:

- Vessel only actively heats while on induction coaster, using alignment magnets.
- When lifted from coaster, phase change material and aerogel lining maintain temperature passively.
- The coaster includes a LED indicated battery level and automatic 2-hour timeout.
- NFC vessel identification tag included to prevent coaster from activating for non-compatible objects.

1.1.8 Exception flow

The exception flow is as follows:

- Fault in temperature maintenance system
- No power available
- Solution not activated

- Physical damage
- Misuse of solution
- Vessel places on coaster without liquid
- Non compatible object on coaster

2 Background

The drinking vessel is one of the most common and oldest household objects but keeping drinks warm has largely remained unsolved in conventional designs. Freshly brewed tea begins cooling immediately upon pouring, and within 15 to 20 minutes its temperature typically falls below the preferred drinking range of 60-65°C [1]. The standard ceramic mug has stayed the dominant domestic design and succeeds in handling hot liquids but disregards heat loss. The vacuum flask, commercialised by Thermos in 1904, was the first significant innovation, manufactured with a double walled construction which dramatically reduced both conductive and convective heat loss. The recent popularity of brands such as Stanley has brought vacuum insulated flasks into mainstream and domestic use, but these designs fail to actively maintain precise temperatures.

A challenge of this report was the over familiarisation of existing products, causing a cognitive bias towards existing solutions. This report maintains it's solution neutrality through systems engineering tools.

3 Systems Engineering Methodology

3.1 The Origins

Grand and complex designs, such as the Great Pyramids or the Roman aqueducts, were built using a systematic and holistic approach. The same thinking that was historically used to achieve great engineering feats is known collectively as system thinking and forms the foundation of system engineering.

The term “systems engineering” was first used in March 1950 in a presentation to the Royal Society of London by the Executive Vice President of Bell Telephone Laboratories, where the speaker attributed it towards the company's success to the same importance level as its research and development programmes [2].

Later, in 1956, the first paper was published on systems engineering by General Motors, where system engineers are described as “on an equal level with other electrical and mechanical design groups” [3]

1962 saw the first Systems Engineering course to taught, at MIT, where it was described as a “transdisciplinary discipline” [4]. In 1995 Nasa published its System Engineering Handbook and in 2005 the International Standards Organization published the first standard to define modern day systems engineering [5].

The international Council on Systems Engineering now defines systems engineering as “a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.” [6]. The main idea is to distinguish what a system must do, from how it should do, and reduce premature bias towards less optimal system architectures.

3.2 Quality Function deployment

Quality function deployment was first developed in the 1960's and first applied by Mitsubishi in 1972. Its purpose is to provide a visual and quantitative framework to ensure traceability to customer needs. It allows for one to score requirement characteristics and their relationship between one another consciously. Two quality function deployment matrixes were used on this report: one to map functional requirements and one to map design requirements, this allowed for the identification of critical requirements and linked them to subsequent features.

3.3 The Single Assessor

The report and study were conducted by one assessor. In an industry, these would be undertaken by multiple stake holders allowing for critiques for each requirement and need. All scoring will include some form of systematic bias and hence multiple assessors would strengthen the credibility of the report.

3.4 Solution Based Engineering?

Solution based engineering means that the final design has already been thought of before any investigation into requirements has taken place. This approach introduces bias and undermines the customer by ignoring their needs. By investigating the requirement set, one can properly fit their solution to what the customer wants.

The first iteration of this report fell into this flaw by defining requirements with a preexisting design in mind. Sullivan emphasises quality function deployments effectiveness to depend on customer needs and not technical specifications [7]. A restructured analysis was performed to be more in line with the systems engineering methodology.

4 Key Customer Requirements

4.1 Use case goal

The use case presented an initial challenge by having to avoid operational details that implied specific solutions. The use case for this report describes what happens rather than how and leaves the mechanism open to interpretation, and can be found in Chapter 1.1 “Use case”.

4.2 Requirement Prioritisation

Nine requirements were prioritised using an analytic hierarchy process pairwise comparison, as seen in Figure 1.

		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	User A wants to enjoy hot beverages at a comfortable drinking temperature for an extended period	User A wants the drinking vessel to be comfortable and easy to handle	User A wants to accommodate varying drink volumes	User B wants the drink to stay warm without active intervention	User B wants the vessel to be visually appealing	User B wants a quiet and unobtrusive experience	User C wants the vessel to be durable and long-lasting	User C wants consistent performance every use	User C wants low maintenance and energy efficiency		Row Product	9th root of row product
1	User A wants to enjoy hot beverages at a comfortable drinking temperature for an extended period	1	2	0.5	0.5	5	2	2	2	2	40	1.50663	13.16
2	User A wants the drinking vessel to be comfortable and easy to handle	0.5	1	0.2	0.2	5	2	0.5	1	1	0.1	0.774264	6.763
3	User A wants to accommodate varying drink volumes	2	5	1	0.5	5	5	2	2	2	1000	2.154435	18.82
4	User B wants the drink to stay warm without active intervention	2	5	2	1	9	5	5	5	2	45000	3.288695	28.73
5	User B wants the vessel to be visually appealing	0.2	0.2	0.2	0.11	1	0.5	0.2	0.2	0.2	4E-06	0.247777	2.164
6	User B wants a quiet and unobtrusive experience	0.5	0.5	0.2	0.2	2	1	0.5	0.5	0.5	0.003	0.513904	4.489
7	User C wants the vessel to be durable and long-lasting	0.5	2	0.5	0.2	5	2	1	2	1	2	1.08006	9.434
8	User C wants consistent performance every use	0.5	1	0.5	0.2	5	2	0.5	1	1	0.25	0.857244	7.488
9	User C wants low maintenance and energy efficiency	0.5	1	0.5	0.5	5	2	1	1	1	1.25	1.025104	8.954

Figure 1: Raw pairwise comparison matrix using analytic hierarchy process. The matrix is reflected along the X/Y axis and inverted.

The comparison uses Thomas Saaty’s nine-point scale [8] to produce normalised percentage weightings. The two temperature related requirements received the highest combined weighting (28.7 and 13.2) and confirmed temperature maintenance to be a dominant need.

A setback of using this pairwise comparison is its subjectivity, as different assessors would produce different rankings. The comparison also assumes for requirement independence. In an ideal environment, multi stakeholder working groups would be carried out to mitigate these limitations.

5 Critical System Functionality

5.1 Decomposition

The nine solution functions were identified with quantified targets. See [Table 1].

Table 1 Solution functions (left), respective quantified targets (right).

Maintain Liquid Temperature	60-65°C for 2+ hours
Contain Liquid Safely	100-350ml
Enable Comfortable Handlings	Material surface below 40°C
Indicate Liquid Status	$\pm 5^{\circ}\text{C}$ accuracy
Resist Thermal loss	$\pm 5^{\circ}\text{C}$ per 30 minutes
Withstand Mechanical Impact	1m drop with no damage
Enable Easy Cleaning	Less than 2 minutes to clean
Supply Energy	4+ hours per charge
Regulate Temperature Output	$\pm 2^{\circ}\text{C}$ accuracy

The identified functions have a quantified target as without measurable benchmarks the scores are only qualitative and unverifiable. These targets are essential for benchmarking if the final design meets the user needs. Furthermore, the functions can be achieved through multiple methods, and this is what allows creative solutions to occur.

Determining the abstractness of each function was a challenge. The aim was to be at a level where each function had a measurable objective with no implied mechanism. This required multiple iterations.

5.2 Quality Function Deployment 1

The House of Quality matrix [Figure 2] shows weighted requirements against functions using relationship scores. Maintaining liquid temperature and regulating temperature output both emerged as the most important functions, both scoring 458. Chan and Wu [9] explain that the primary value in quality function deployment is that it forces systematic consideration of all requirement function pairs.

How	Importance	Maintain liquid temperature	Contain liquid safely	Enable comfortable handling	Indicate liquid status	Resist thermal losses	Withstand mechanical	Enable easy cleaning	Supply energy	Regulate temperature output
Requirements										
User A wants to enjoy hot beverages at a comfortable drinking temperature for an extended period	13	9	1	1	3	9			3	9
User A wants the drinking vessel to be comfortable and easy to handle	6.8		1	9		1				
User A wants to accommodate varying drink volumes	19		9	1	1			1		
User B wants the drink to stay warm without active intervention	29	9			3	9			3	9
User B wants the vessel to be visually appealing	2.2		1	1	3			1		
User B wants a quiet and unobtrusive experience	4.5	1							1	1
User C wants the vessel to be durable and long-lasting	9.4		3	1		1	9	1		
User C wants consistent performance every use	7.5	9	1		3	3	1	3	3	9
User C wants low maintenance and energy efficiency	9	1				3		9	9	1
		458	227	104	173	443	92	133	233	458

Figure 2: House of Quality matrix for QFD 1.

5.2.1 Table and Chart: analytical tools and communicational tools.

Whilst the matrix shows the complete relationship, the functional importance ranking is more readily interpreted as a bar chart [Figure 3]. Tabular matrices are great for capturing relationships, but graphical and visual representations are

more effective for communicating priorities and patterns to others (such as stakeholders) (10).

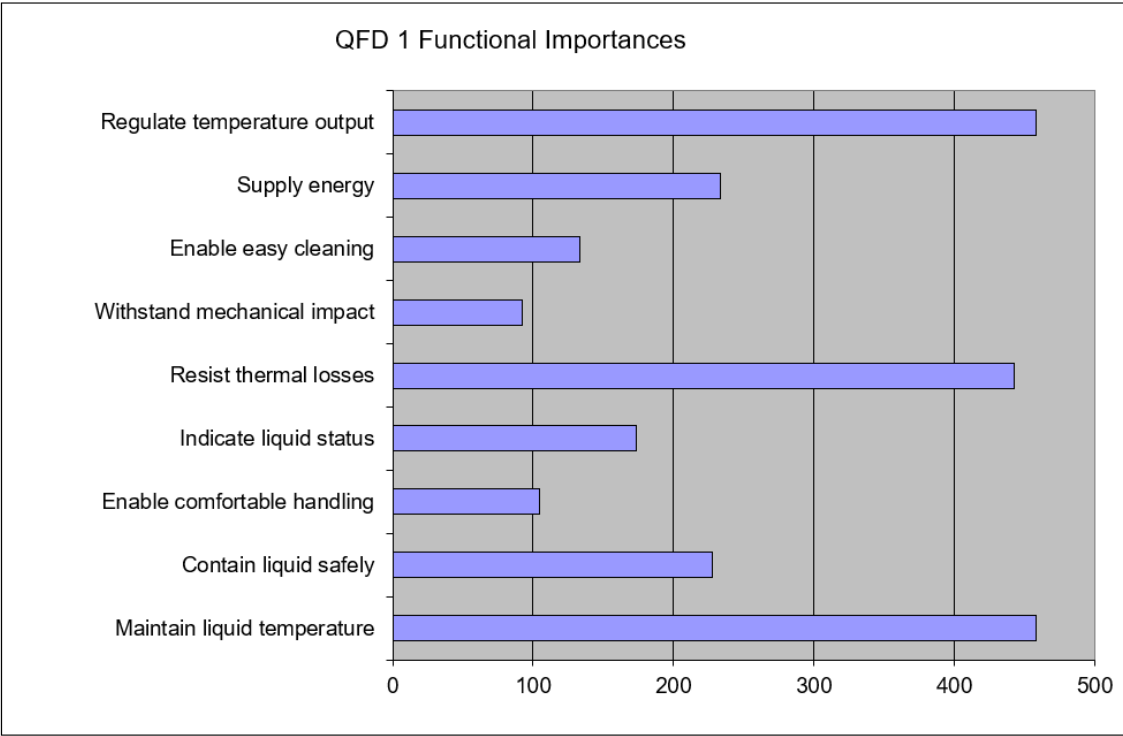


Figure 3: House of Quality Functional Importance Grap for QFD 1

5.3 Testing functional metrics

The functional metrics matrix [Figure 4] extends the quality function deployment by mapping each requirement against known testing methods to allow for objective verification. Out of the 9 metrics gathered, the most important identified were temperature retention and temperature regulation (both 458).

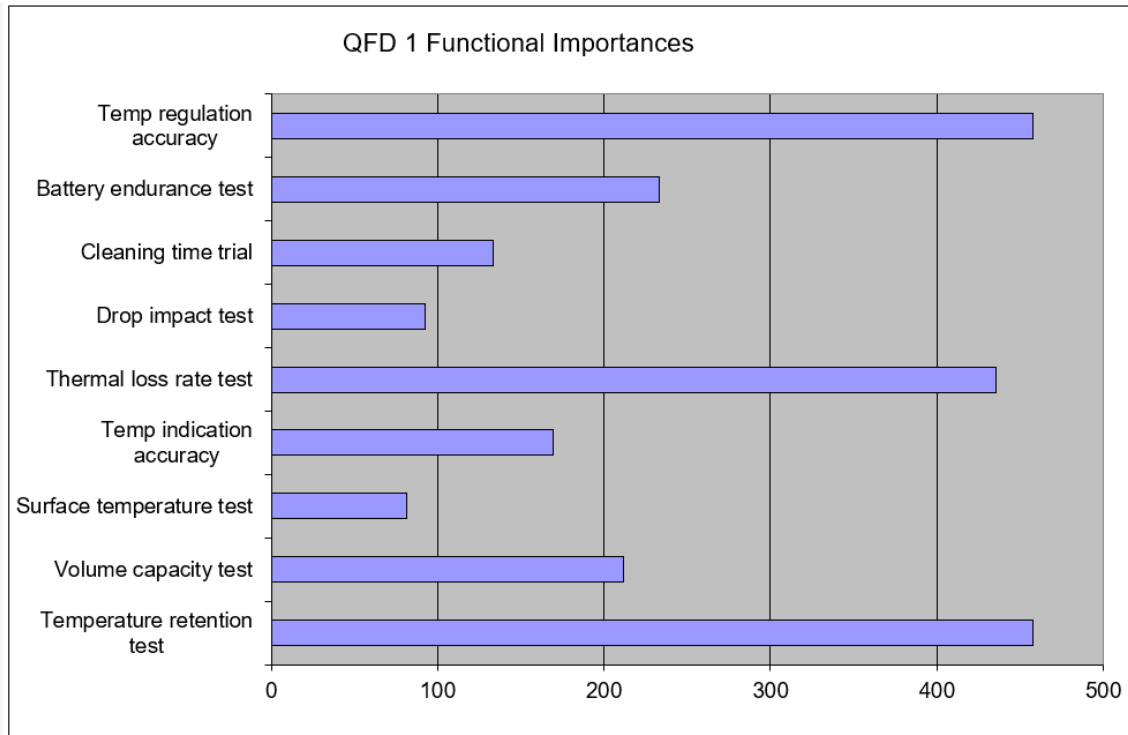


Figure 4: Functional importances graph for Functional Metrics

6 Concept Derivation and Design Choices

6.1 Function Means Analysis

The function means analysis [Figure 5] explores three alternative means (v1, v2, v3) for each function. The complete sets were assembled into distinct concepts for Pugh evaluation against a ceramic mug datum, ensuring that each concept is coherent. The benefit of this is that it prevents early commitment and allows the designer to use their engineering skills to think of novel and creative ideas for each function without looking at how they would yet interface. This drives for a better solution, as it eliminates any preconceptions of how things are put together.

	v1	v2	v3
Maintain liquid temperature	Vacuum insulation (passive)	Electric heating element (active)	Phase-change material lining
Contain liquid safely	Stainless steel vessel	Ceramic vessel	Borosilicate glass vessel
Enable comfortable handling	Integrated handle	Double-wall air gap	Silicone grip sleeve
Indicate liquid status	Thermochromic colour-changing coating	Digital temperature display	LED indicator ring
Resist thermal losses	Vacuum double wall	Foam insulation	Aerogel lining
Withstand mechanical impact	Stainless steel construction	Silicone bumper casing	Reinforced polymer shell
Enable easy cleaning	Smooth non-porous interior	Removable inner liner	Antimicrobial coating
Supply energy	No energy required (passive only)	Rechargeable battery (internal)	Induction charging from coaster
Regulate temperature output	No regulation (passive retention)	Thermostat-controlled heating element	Self-regulating PTC heater

Figure 5: Function Means Analysis table showing all 3 concepts.

6.2 Concept Assembly and Pugh Matrix Evaluation

The Pugh Matrix [Figure 6] scored each concept against the nine initial user requirements on a scale of -2 to +2, relative to the ceramic mug datum.

		Relative Importance Equal	Relative Importance Weighted	Current Design	Standard Ceramic Mug (Benchmark)	Vacuum-Insulated Passive Mug	Self-Heating Cup with Internal Battery	Induction Coaster System
WHATs – Customer Requirements	How much: – From QFD 1							
User A wants to enjoy hot beverages at a comfortable drinking temperature for an extended period	3.363681056	5	13.16	0	0	1	1	2
User A wants the drinking vessel to be comfortable and easy to handle	11.79241041	5	6.763	0	0	0	-1	0
User A wants to accommodate varying drink volumes	20.67094666	5	18.82	0	0	0	0	0
User B wants the drink to stay warm without active intervention	24.43090385	5	28.73	0	0	1	1	2
User B wants the vessel to be visually appealing	4.74212377	5	2.164	0	0	0	1	1
User B wants a quiet and unobtrusive experience	9.359642349	5	4.489	0	0	0	-1	1
User C wants the vessel to be durable and long-lasting	9.359642349	5	9.434	0	0	2	2	1
User C wants consistent performance every use	7.827010564	5	7.488	0	0	1	1	1
User C wants low maintenance and energy efficiency	8.453638986	5	8.954	0	0	1	-2	-1
Development Cost		5	10	0	0	0	1	0
Purchase Cost		5	10	0	0	0	1	-1
Availability		5	10	0	0	1	1	0
				0	0	35	25	30
				0	0	87.2	71.25	88.3964136
Ranking		100		0	0	-52.2	-46.2	-58.3964136

Figure 6: Pugh matrix for all three concepts, including scores.

Using equal weighting across all criteria including cost factors, the v1 solution appeared to be the strongest concept with an unweighted total of 35. The v1 concept benefits greatly from its strong scores on durability and has no negative scoring. However, when the requirement weightings are applied, the ranking changes to favour the v3 concept. V3 has a weighted requirements score of 88.4, as compared to the 87.2 for v1. The shift in score occurs as the two highest weighted requirements (staying warm without active intervention and enjoying hot beverages at temperature) account for over 40% of the total weighting, for which the v3 concept scores a +2 on both. The v1 concept only scores +1 on these as the vacuum mug concept can't actively reheat liquids. This demonstrates the value of the analytic hierarchy process, as the perfect solution should consider how important each requirement is to the users.

The Pugh matrix also includes cost and availability factors which are scores separately from user requirements. These are practical considerations and show a distinction in systems engineering between what best meets user needs and what is most practically achievable. The concept selection prioritises the user

requirements with cost and manufacturability treated as constraints to be addressed during design rather than issues in concept selection.

Pugh states that the matrix allows for controlled convergence through successive evaluation iterations [11]. The method itself is, however, self-limiting. This is highlighted when looking at safety critical features: some solutions may be less safe to use but will fit the user requirements better. A solution to this may be to include safety as a user requirement and set a weighting to this agreed to by multiple different stakeholders.

6.3 The winning concept

The winning concept is the v3 solution. It contains: phase change material, borosilicate glass, silicone grip sleeves, LED indicator ring, aerogel lining, reinforced polymer shell, antimicrobial coating, induction charging coaster, self-regulating heater.

The v3 concept separates the energy source from the drinking vessel and allows for passive operation if the coaster fails. It has phase change material which provides thermal buffering and aerogel that minimises loss.

This solution may not be the best, however, as it does score negatively on some of the requirements whereas other concepts have no negative scores. This would be something to raise in a stakeholder meeting and to discuss with the user further.

7 Potential Failure modes

7.1 DFMEA Methodology

A DFMEA was performed on the winning v3 concept following Statmis [12], examining each function across 5 failure categories. Each mode was scored for severity, occurrence and detectability. At the concept stage these scores are only speculative rather than empirical, meaning that the DFMEA serves as design guidance only. The full DFMEA is provided in [Appendix A].

7.2 Critical Failure Modes

The highest severity is from a vessel fracture (severity 8). This is because the borosilicate vessel will produce large shards of glass when it breaks and cause the hot liquid inside to come out. However, there is mitigation in place with a reinforced polymer shell that absorbs impact and contains fragments.

If the coaster fails, the vessel will function passively and retain its charge and slow down heat loss due to the aerogel and phase change material. This is an architectural advantage of separating out the heating element.

8 Critical Design Features

8.1 Quality Function Deployment 2

Another House of Quality matrix was used to map functions against the nine v3 design features [Figure 7]. The importance ranking shows phase change material lining (948) and self-regulating heater (946) as the most critical, followed by aerogel lining (833). Antimicrobial coating scored the lowest (143). This ranking is consistent with the methodology, as the highest-ranking requirements drive the highest-ranking functions, which in turn drive the highest-ranking design features. This, however, is not self-correcting and allows for the propagation of poorly scored ideas throughout the design process.

Design feature	Importance		Importance	Phase-change material lining	Borosilicate glass vessel	Silicone grip sleeve	LED indicator ring	Aerogel lining	Reinforced polymer shell	Antimicrobial coating	Induction charging from coaster	Self-regulating PTC heater
Functionality												
Maintain liquid temperature	458	10	46	9				9			3	9
Contain liquid safely	227	10	23		9			1	3	1		
Enable comfortable handling	104	10	10			9			3			
Indicate liquid status	173	10	17		3		9				1	3
Resist thermal losses	443	10	44	9		1		9	1			
Withstand mechanical impact	92.4	10	9		1	3			9			
Enable easy cleaning	133	10	13		3	1			1	9		
Supply energy	233	10	23								9	3
Regulate temperature output	458	10	46	3			1				3	9
				948	306	179	202	833	240	143	502	946

Figure 7: House of Quality matrix for QFD 2.

8.2 P-Diagram and What-Why

The P diagram [Figure 8] identified 10 control factors and 18 noise factors.

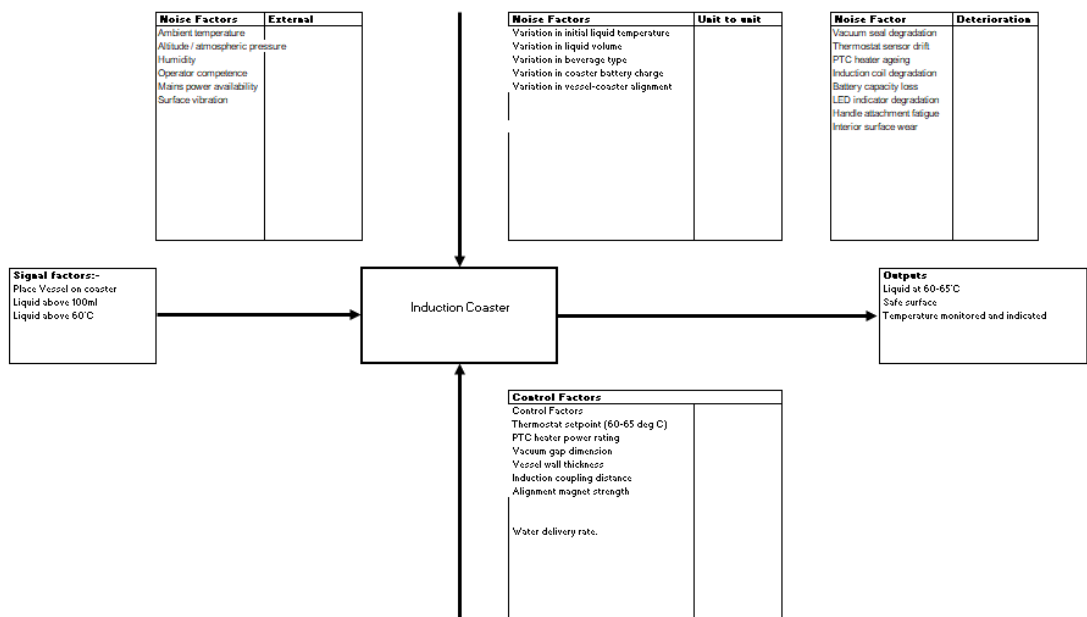


Figure 8: P-Diagram for the induction coaster system.

The resulting What-Why analysis [Figure 9] showed ambient temperature as the most significant noise factor (210), followed by initial liquid temperature (189) and thermostat drift and self-regulating heater (108), which can be seen in the noise factor importance ranking [Figure 11].

	Weighting of design parameter	NOISE FACTORS																	Relative Importance of noise in meeting performance via control factor		
		Unit to Unit Variation					Deterioration								External					Total	
		Control	Control	Control	Control	Control	Mig	Mig	Mig	Mig	Mig	Mig	Mig	Mig	Environ- ment	Environ- ment	Human	External			External
		Variation in initial liquid temperature	Variation in liquid volume	Variation in beverage type	Variation in coaster battery charge	Variation in vessel-coaster alignment	Vacuum seal degradation	Thermostat sensor drift	PTC heater ageing	Induction coil degradation	Battery capacity loss	LED indicator degradation	Handle attachment fatigue	Interior surface wear	Ambient temperature	Humidity	Operator competence	Mains power availability			Surface vibration
Design control parameters																					
Thermostat setpoint (60-65 deg C)	9	3		3				9						3	1				31	279	
PTC heater power rating	9	9	3	3					9	3				9					36	324	
Vacuum gap dimension	9						9							3	1			1	14	126	
Vessel wall thickness	9	1										3	3			1			8	72	
Induction coupling distance	3					3				9								3	21	63	
Alignment magnet strength	3					9										3		3	15	45	
Battery capacity (Wh)	3				3					9				3			3		30	90	
Over-temperature cutoff (70 deg C)	3	3						9	3					3					24	72	
Handle thermal break material	3	3										9		1					13	39	
Interior surface finish	3			3												3			15	45	
Relative importance of noise factor:		189	27	63	27	54	81	108	108	54	27	0	54	54	210	18	27	27	27		

Figure 9: What-Why matrix including scores.

The most significant control factor was the self-regulating heater power rating (324), followed by thermostat set point (279) and vacuum gap dimensions (126), which can be seen in the control factor importance ranking [Figure 10].

A limitation of P-Diagrams is that it focuses on a single cause rather than combined effects. A combination of things may produce a failure that is not caused by one alone, requiring a more advanced design of experiments to capture.

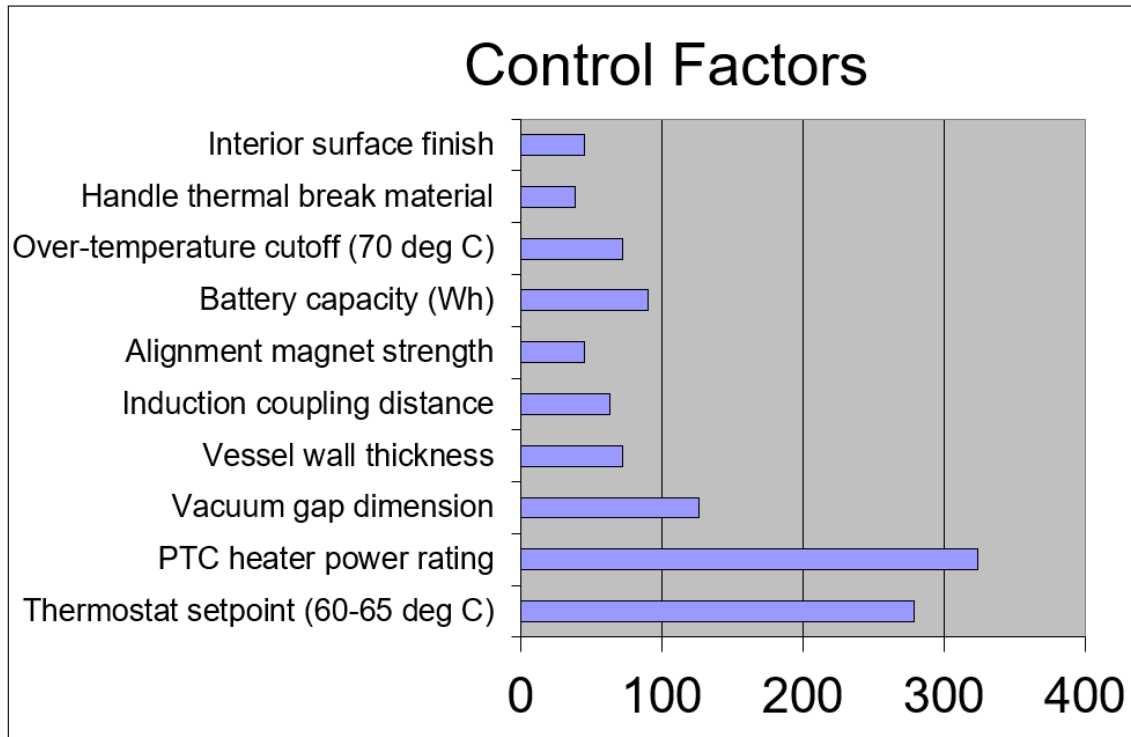


Figure 10: Control factor graph for the v3 concept.

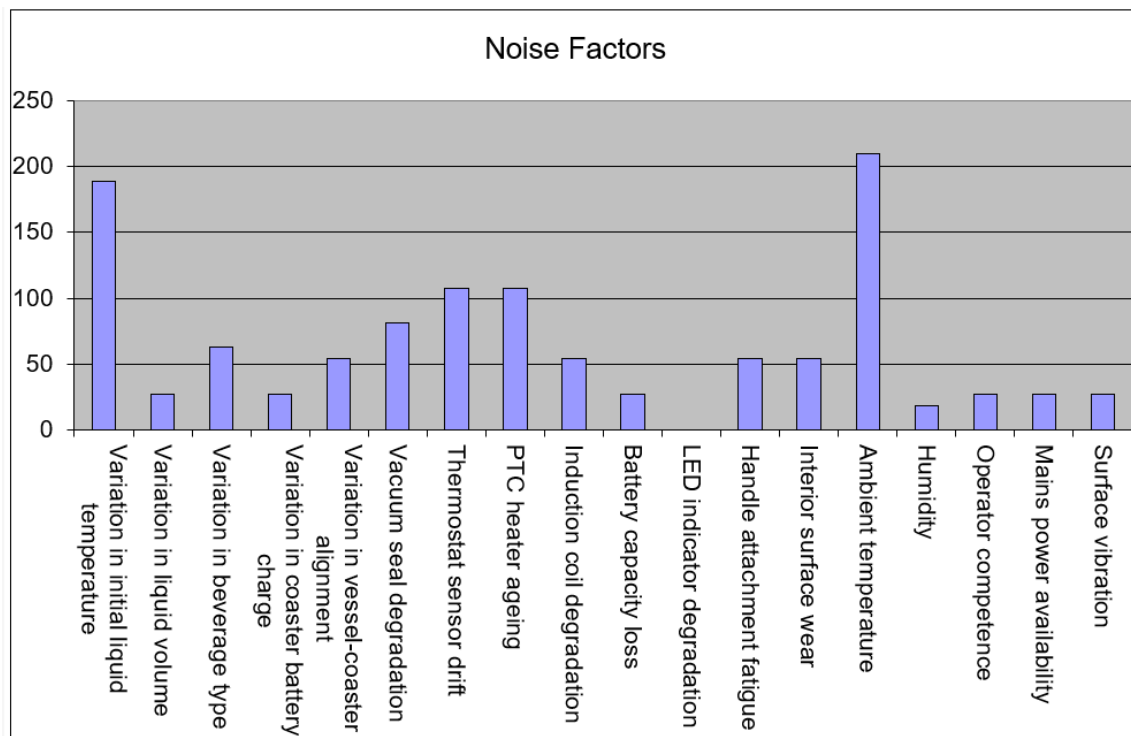


Figure 11: Noise factor graph for the v3 concept.

9 Conclusion

The study was successful in picking out a solution neutral concept for drinking and maintaining hot beverages at hot temperatures.

Systems thinking allowed for this report to stay solution neutral, but the systems engineering tools used allowed for this to be used to find the correct solutions and requirements. The initial requirements importance ranking was the most useful part of the toolset, as this influenced every other stage of the report. The initial requirements produce a weighted value which drastically effects which function gets prioritised. This can be seen in the Pugh matrix, as when the weighted values were used the winning idea was changed to a different concept. Both QFD 1 and QFD 2 were also equally important, as they steered the design choices towards a more user dependent solution and helped to uncover what functions were the most important when compared to the requirements.

Systems engineering has been used officially for almost a century, with undocumented uses going as far back as the great pyramids. This tool allows users to solve complex systems and turn them into multiple easier decisions. However, systems engineering requires multiple inputs and iterations to work which this report did not cover. For future studies, this report suggests that users discuss each step within a diverse group, including initial users, to reduce bias and uncover more concepts and requirements that this report could ever have through a single assessor.

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Appendices

Appendix A – DFMEA table

See below for DFMEA:

Function	Failure Mode	System effect	Effect Seen by user	Severity	Cause	Mechanism (If Known)	Occurrence	Detection / prevention method	Detectability	Rating	Comment
Maintain liquid temperature	Over function	liquid exceeds 65 deg C	Drink is too hot to consume safely, potential scalding	6	heater overcharges		4	temperature cutoff at 70 deg	3	72	
	Under function	liquid falls below 60 deg C	Drink feels lukewarm, not maintained at desired temperature	2	thermal capacity degraded		5	Temperature indicated by LED ring alerts user	4	40	
	No function	liquid cools naturally	Drink goes cold as if using a standard mug	3	Complete failure of induction charging		3	Alerts user	2	18	
	Intermittent function	Temperature fluctuates outside 60-65 deg C range	User notices drink alternating between warm and cool	3	Uneven distribution of material within lining		4		4	48	
	Unintended function	release heat when vessel is empty or contains non-liquid items	Empty vessel remains hot, burn risk if touched internally	4	liquid is consumed with no volume detection		5	Warning label instructs user	5	100	
Contain liquid safely	Over function									0	
	Under function	Micro-cracks	User notices dripping or wetness on exterior of vessel	4	heating and cooling cycles		3	Visual inspection of glass vessel	3	36	
	No function	vessel fractures, liquid escapes completely	Hot liquid spills, potential burn and laceration hazard from glass shards	8	Impact damage or severe thermal shock		3	drop test certification to 1m	3	72	
	Intermittent function	Slow seepage only occurs when vessel is at operating temperature	Occasional dripping noticed during heating cycles	3			3	Thermal cycling test during manufacture	4	36	
Enable comfortable handling	Unintended									0	
	Over function	Silicone sleeve provides excessive grip, vessel difficult to release from hand	User struggles to put vessel down or adjust grip	1	Silicone material too grippy		2	Material selection testing	3	6	
	Under function	Silicone sleeve transfers heat to user hand or provides insufficient grip	User feels discomfort from heat or vessel slips during handling	5	Sleeve too thin or degraded		4	Material selection testing	3	60	
	No function	Silicone sleeve detaches from vessel during use	User loses grip, vessel may fall and shatter, spilling hot liquid	7	Adhesive failure		2	Material selection testing	3	42	
	Intermittent function	Sleeve loosens and shifts during use	Vessel feels insecure in hand, reduces user confidence	3	Thermal cycling		3	Material selection testing	3	27	
										0	

Figure 12: APPENDIX: DFMEA Part 1.

Indicate liquid status	Over function	LED indicates temperature higher than actual liquid temperature	User believes drink is hotter than it is, waits unnecessarily	2 Sensor calibration error		3 Sensor placement optimised during design	3	18
	Under function	LED indicates temperature lower than actual liquid temperature	User may drink liquid that is dangerously hot	5 Sensor contamination		3 temperature cutoff	3	45
	No function	LED fails to illuminate	User has no visual temperature information but vessel still heats normally	2 loose connection		3 fault is visually obvious	2	12
	Intermittent	LED flickers or shows inconsistent colour	User cannot trust temperature indication	2 Loose connection to LED		4 Connections secured with coating	4	32
	Unintended	LED displays wrong colour for actual temperature	User confused by incorrect status	2 Firmware error		2 Firmware validation testing	3	12
Resist thermal losses	Over function		Drink cools faster than expected, no heater works harder draining coaster					0
	Under function	Aerogel insulation degraded	Drink cools faster than expected, no heater works harder draining coaster	3 Aerogel lining damaged		4 Aerogel protected	4	48
	No function	Complete loss of insulation	Drink cools rapidly; external surface may become hot to touch	5 Aerogel lining completely damaged		2 Sealed construction prevents water leakage	3	30
	Intermittent							0
	Unintended							0
Withstand mechanical impact	Over function							0
	Under function	Polymer shell cracks	Cosmetic damage	4 wall too thin		3 Drop test from 1m	3	36
	No function	Polymer shell shatters	Complete failure, hot liquid spillage, glass shard and burn hazard	8		2 Drop test from 1m	3	48
	Intermittent							0
	Unintended							0

Figure 13: APPENDIX: DFMEA Part 2.

Supply energy	Over function	Coaster delivers excessive power	overheat, potential fire risk or glass thermal shock	7 Power failure in coaster		2 Thermal fuse	3	42
	Under function	Insufficient power transferred to vessel	heater cannot fully charge, temperature maintenance is weak	2 Coaster battery depleted		4 Battery level indicator	2	16
	No function	No power transferred to vessel	System does not heat; vessel relies on residual heat and aerogel insulation only	3 Coaster battery fully depleted or charger fault		5 Clear battery status	2	30
	Intermittent	Power delivery drops in and out	charges unevenly, temperature fluctuates	3 Poor alignment between coaster and vessel base		5 Alignment magnets	3	45
	Unintended function	Coaster attempts to heat non compatible object	Foreign metallic object on coaster could overheat, potential fire risk	6 Non compatible object on coaster		3 NFC vessel identification	2	36
Regulate temperature output	Over function	heater self regulation point above 65 deg C target	Drink too hot, potential scalding risk	6		3 Factory calibration of each unit	3	54
	Under function	heater self regulation point below 60 deg C target	Drink cooler than desired	2 temperature set too low from manufacturing variation		3 Factory calibration	3	18
	No function	heater fails to generate heat despite receiving power	No temperature regulation, liquid cools passively through aerogel insulation	3		3 LED indicator shows power received but no temperature rise, alerting user	3	27
	Intermittent	heater output oscillates	User notices temperature cycling during uneven heating; drinks hot and cold	3 Cracked element or loose electrical connection to heater		4 Connections designed with strain relief	4	48
	Unintended function	heater generates heat in localised hotspot	uneven heating; drinks hot and cold; base in liquid; base of glass vessel thermally stressed	4 element partially separated from base		3 Thermally conductive adhesive	4	48

Figure 14: APPENDIX: DFMEA Part 3.

