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Design Portfolio Activity

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Abstract

This report is to identify a required improvement to a kitchen appliance and design a solution using complex systems engineering methods to analyse, design and assess a chosen solution. This will include the use of complex tools and strategies such as pairwise analysis, functional means analysis, Quality Function Deployment (QFD), functional importance graphs, functional metrics, system Pugh matrix, identification of potential failure modes, and finally critical design features leading into QFD2.

Keywords:

Systems engineering, quality function deployment, pairwise, potential failure modes, pugh matrix, design functionality, critical system design.

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List of Abbreviations

DFMEA	Design Failure Mode Effect Analysis
DoD	Department of Defence
QFD	Quality Function Deployment

1 Systems Engineering

Systems engineering is a complex process in which an issue or opportunity is identified in order to increase capability via the use of a new system, refining an existing system, or resolving a problem with a system. It uses tools, analysis and problem solving skills in order to ensure the proposed solution is not only right as per the key customer requirements, but also attempts to identify any problems or fallbacks and mitigate against them ahead of the final design acceptance, thus ensuring that whilst the right thing has been designed, the thing has been designed right (also seen as design the right thing, then design the thing right!).

Systems Engineering was first coined in 1950 at MIT by George W. Gilman, Director of Systems Engineering at Bell Telephone Laboratories, although its concepts can be traced back to the early 1900s, with the most major applications in history being used during World War II.

It is described to have 5 phases:

1. System studies or program planning
2. Exploratory planning, which includes problem definition, selecting objectives, systems synthesis, systems analysis, selecting the best system, and communicating the results
3. Development planning, which repeats phase 2 in more detail
4. Studies during development, which includes the development of parts of the system and the integration and testing of these parts
5. Current engineering, which is what takes place while the system is operational and being refined.

The Department of Defense (DOD) was first recorded to have used systems engineering in the late 1940's to develop missiles and missile defence systems [1].

2 Key Customer Requirements

For the purpose of this report, it was first important to identify a simple household object which could benefit from systems engineering in order to resolve an issue.

This includes understanding what the object is supposed to do, how it performs that function, where there may be an issue or opportunity to improve said function and ensuring that any improvements do not hinder the original function, either by reducing functionality, reducing user understanding, or inhibiting functionality altogether.

The object which was identified was the kitchen toaster, which had three users, all of whom had different preferences for their end product. The three user end product requirements were:

1. Barely toasted bread
2. Golden brown toasted bread
3. Dark brown toasted bread

The toaster itself had a dial control on the side to adjust level of toastiness, however the manual adjustment created more than a few disagreements in the household, where users wouldn't check the level prior to use and then complain once the bread had been toasted to an unsatisfactory level, as per their preferences.

As a result, a set of key customer requirements were gathered, and could be broken down into four categories:

- Non-functional performance requirements
- Functional requirements
- Non-functional implementation requirements
- Non-functional system requirements

This breakdown allows a deeper understanding of outlining what things the object must have in order to function correctly but also understand the full capability of what it should have to meet customer requirements, could have to prevent issues and won't have as they are the lowest priority but may be considered for future

iterations. This prioritization is known as MoSCoW, and whilst it provides clear, simple prioritisation with effective resource allocation, it lacks granularity when breaking down the development of the object and can lead to misinterpretation of the 'won't have' priority.

Ensuring these requirements were looked at also meant an engineering approach could be taken to ensure engineers were able to identify aspects of the project which the customer may not. This minimised any result of issues and cost to fix, should there be an issue with the final product design, as it is cheaper and easier to fix issues if identified earlier in the project.

Identifying the correct categories for these requirements allowed the use of the further breakdown of object components, in which a method called 'crossing the V' was used. This V can be seen in [Appendix 1](#). This method allows for understanding the issue right down to its basic form, allowing definition of requirements in detail before any technological choices were made.

Other requirements outlined were identified from the attributes as follows:

- People
- Processes
- Tools and techniques

Where the user and use were considered as variables and therefore important to the gathering of requirements to ensure correct product development.

People are important as they are the users of the object, but also different people like to use the same product in different ways, as outlined by the user end product requirements. They are also important as the more people you have contributing, the more likely you are to understand shortfalls and avoid missing requirements.

Processes are equally important, as the processes must follow simple step-by-step instructions, not just for the use of the product, but also for the installation and maintenance, they tell you what to do and when to do it, although they do not specify how to do it.

Tools and techniques allow the analysis of how the end product may be achieved, as well as used, adjusted, broken and fixed in the event of a catastrophic failure. It is important to understand that Systems Engineering tools are, in principle, communicative and allow different disciplines to explore systems issues.

In order to understand the best solution to meet our user requirements, it is also important to understand the functions required in order to produce the required outcome. This can be done via the use of a functional decomposition, listing out the functional system processes which make up a successful system process execution.

For the outcomes identified by the prior key customer requirements the existing object current operations can be identified as well as any additions or changes to the process which may change the operation to achieve the required outcome.

Step no.	Existing process	Solution process
1.	Bread acquired from supplier	Bread acquired from supplier
2.	Bread placed in toaster	Bread placed in toaster
3.	Setting set and does not change throughout process	Toaster lever pushed down and automatically locked into place
4.	Toaster lever pushed down and automatically locked into place	Setting set, setting returns to unset after use
5.	Heating element engages	Heating element engages
6.	Once sufficient heat has been supplied, toaster disengages heating element and toaster lever unlocks, springing toasted bread upwards	Once setting has been satisfied by the toaster, toaster disengages heating element and toaster lever unlocks, springing toasted bread upwards
7.	Toasted bread is removed and used in desired manner	Toasted bread is removed and used in desired manner

Table 1 - Process Step Comparison

From this, some MoSCoW requirements prioritisations have been derived and can be seen in the table in [Appendix 2](#).

3 Critical Systems Functionality

When analysing the breakdown of requirements from [Appendix 2](#), having applied the MoSCoW prioritization, the critical systems functionality can be seen clearly, as they fit under 'must' category. As it is increasing the capability of an existing product, the 'should' category must also be taken into account, to ensure the end product satisfies the requirement.

The requirements are as follows:

- The toaster must be compatible with standard UK power supply
- It should be easy to identify in a kitchen setting
- The improved control of toastiness must be intuitive to use to prevent user error
- In turn, it should be easy to adjust the settings, to satisfy user requirements
- The bread must be of a suitable thickness for use in toaster (however this could be incorporated into the toaster design, i.e. thicker bread slots)

If any of these requirements are not met, it will result in critical failure of the system.

These functions can also be identified as resolutions to a multiple cause diagram, as described in [Appendix 3](#), of which identifies issues which may cause failure of the system.

Another way to identify prioritization and critical systems functionality is to use a pairwise technique, which identifies critical systems parameters and compares them against each other. In turn this provides a scoring that identifies a prioritization or ranking order, where higher scoring can either identify a higher priority (as in this case of using it for a benefit/functionality scale), or at a lower priority (in the case of a cost or risk scale) [2]. A pairwise for the critical system functionality has been collated and can be seen in [Appendix 4](#) which identify the priority of the requirements derived from critical system functionality analysis, as identified from the MoSCoW prioritisation. Whilst this offers a deeper

understanding of the prioritisation of the critical systems functionality, all of these functions are, by nature, critical, and therefore will all still need to be met, although it does help when choosing a suitable solution.

As a result of this, a comparison of the identified critical systems function against the key user process for the solution has been compiled into Quality Function Deployment (QFD) 1, located in [Appendix 5](#).

4 Concept Derivation and Design Choices

Three potential solutions were presented as ideas to meet key customer requirements:

Twist knob timer – This basic and intuitive solution is to adapt an existing model with a twist knob timer, where the toaster would not begin toasting until the timer had been turned to a required timing setting. As an adaptation to an existing product which relies solely on mechanical parts and not electrical power (although does form part of the critical electrical system for functionality), this is the least complex and most cost-effective choice.

Digital timer and touch screen interface (including user profiles) – This solution included installing a touch screen interface which allowed user profile creation where the primary mechanism for ensuring preferred toastiness for the specific user is controlled via a digital timer. The ability to create a user profile allowed users to easily select their own profile to attain the same level of toastiness time and time again.

Optical sensor and touch screen interface (including user profiles) – This solution is by far the most complex and least cost effective, with the previously mentioned touch screen interface and user profile creation also being utilised, but instead of a timer this solution incorporates an optical sensor which analyses and assesses the toastiness of the bread based on its appearance, offering the highest level of accuracy.

These three solutions were carefully analysed and evaluated against both critical functionality requirements and key customer requirements, as well as compared using any unseen advantages and drawbacks.

Concept mock-ups of these designs can be seen in [Appendix 6](#).

4.1 Twist knob timer

Comparing this design to the critical systems functionality requirements , it is understood that it easily meets the criteria, as it is a mechanical function there is no change to the power requirements, nor the overall functionality or identification of the toaster, except to remove the ability to mistakenly have the toaster on the wrong setting, which satisfies a key customer requirement.

Parts and labour for this is cheap and it is easy to adjust a pre-existing unit, with minimal invasiveness to the overall circuitry.

A drawback to this design is that a twist knob setting adjustment isn't particularly accurate and leaves a potential margin for error. Also, it doesn't allow for user profiling, therefore users will require memory, where for a first time use it can be tricky to identify exactly how to set it, with a possible trial and error testing period per user, which could lead to wastage of bread through errors.

4.2 Digital Timer and Touch Screen Interface Including User Profiles

This design easily addresses the key customer requirements by allowing the creation of user profiles to adequately satisfy any convenience needs, as well as using a digital timer, providing a higher level of accuracy as the timer can be precisely set.

Comparing against the critical systems functionality requirements, there are some complex challenges which will need to be met, namely ensuring the power distribution is correct as the interface and digital timer will require an extra lever of current supply. Whilst the control of toastiness brings a higher level of accuracy, the user interface is more complex and therefore may be less preferred to that of a simple mechanical twist knob timer for installation.

Other drawbacks include the increased requirement for space, as a touch screen interface needs to be large enough to allow the user to easily input commands and controls without mistake.

4.3 Optical Sensor and Touch Screen Interface Including User Profiles

This design provides the highest level of accuracy, as there is no trial-and-error period to identify the correct settings, but instead the user would simply select the setting as per given on the touchscreen and the optical sensor would monitor the surface of the bread to ensure the required level of toastiness is satisfied.

Drawbacks to this design are many in number, including a complex design requiring extra power distribution to sensors and the interface, as well as control and feedback signals between the interface, the heating element and the optical sensors. Other drawbacks include the requirement for maintenance of the optical sensors to ensure maximum accuracy at all times, as dirt, grease and general buildup of material on the sensor could cause inaccuracies or complete failure of the design.

It will also be costly to set up and ensure the software was programmed so that the use and control of the toaster is easy to understand.

4.4 Design Choice

By carefully analysing these designs and comparing them against the functional system requirements, a system pugh has been put together to identify a design choice. This can be seen in [Appendix 7](#).

The result is that, compared to the other designs, the digital timer is the most intuitive with the least complexity, therefore providing a useable solution to the user due to its accuracy and ability. This solution also provides a medium level of cost assurance compared to the optical sensor solution.

5 Potential Failure Modes

Functional failure mode analysis forms an important part of the analysis of the chosen design against critical system functionality requirements, as it identifies potential failures and mitigations against those failures, allowing greater understanding and clarity when choosing a suitable solution.

It can be split into four categories:

- Functional – how could the system functions fail?
- Process – how could the process(manufacturing) fail?
- Use – how could the product fail in use?
- Design – how could the product design fail?

This only identifies the categories in which a failure may exist, but does not specify the type of failure mode, of which there are only 5 modes:

- Over function
- Under function
- No function
- Intermittent function
- Unintended function

ALL failures exist inside these 4 categories and 5 modes.

In order to perform functional failure mode analysis across the critical system functionality requirements, a Design Function Means Effect Analysis (DFMEA) table has been completed for the critical system functions and can be seen in [Appendix 8](#).

With this, aspects of the design requirements can be understood in terms of their importance and priority in order to meet user requirements.

6 Critical Design Features

For the chosen solution, the critical design features are as follows:

- A digital timer for highly accurate timing when setting a program on the toaster
- A touch screen interface to allow clarity of time remaining, user setting visibility and user profile setup
- An internal program function which prevents the user from toasting without setting the program first

This provides a high and consistent level of accuracy, whilst maintaining a relatively low cost for parts and implementation.

The major critical design feature is that the way in which it operates prevents the user from using the system without setting it to their desired requirement first, preventing issues with user requirement incompatibility.

It does this by not engaging the heating element until a time or profile has been selected by the user. At defined stages of manufacture there will be user acceptance tests to ensure it meets critical system function requirements of useability, as outlined by the DFMEA table.

QFD 2 can be seen in [Appendix 9](#), where the system functions have been compared to the critical design features to understand the importance of each design feature and prioritise them appropriately, where it outlines that the touch screen interface forms the most important part of the critical design features for making an improvement.

7 Summary

In summary, a brief history and use of systems engineering has been given, as well as a number of systems engineering tools, identifiers and figures used to identify, describe and compare solutions to a household engineering issue. In turn this allowed the identification of a suitable solution from concepts given, comparison of functions against potential failure modes as well as analysis and prioritisation of the critical design features presented by the solution.

8 References

- [1] D.Buede. The Engineering Design of Systems: Models and Methods. 2000. Available at <https://www.incose.org/about-systems-engineering/history-of-systems-engineering>. Accessed 20251222.
- [2] D. R. Kuhn, R. N. Kacker, and Y. Lei, *Introduction to Combinatorial Testing*, 1st ed. Boca Raton, FL, USA: CRC Press, 2013. Available at <https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-142.pdf>. Accessed 20251228.

9 Appendices

9.1 Appendix 1 – Crossing the V

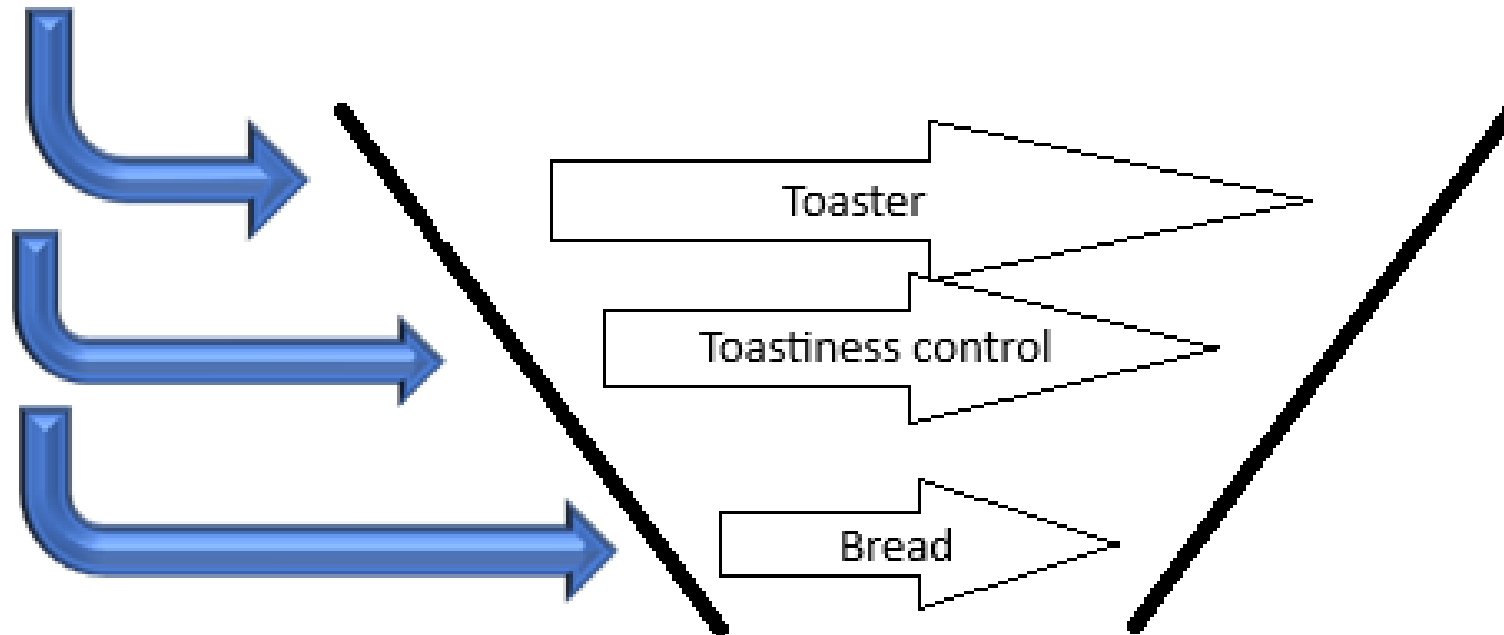


Figure 1 - Crossing the V Component Breakdown

9.2 Appendix 2 – Table of Requirements with MoSCoW Prioritisation

Breakdown	Requirement 1	Requirement 2	Requirement 3	Requirement 4
Toaster	Must be compatible with standard UK power supply	Should be easy to identify	Could have an extended number of slots to toast more slices of bread at once.	
Toastiness Control	Must be intuitive to use	Should be easy to adjust the settings	Could include profiles for regular users	Could allow different levels of toastiness in different slots at once.
Bread	Must be of a suitable thickness for use in toaster.			

Table 2 - Table of Requirements with MoSCoW Prioritisation

9.3 Appendix 3 – Multiple-Cause Diagram

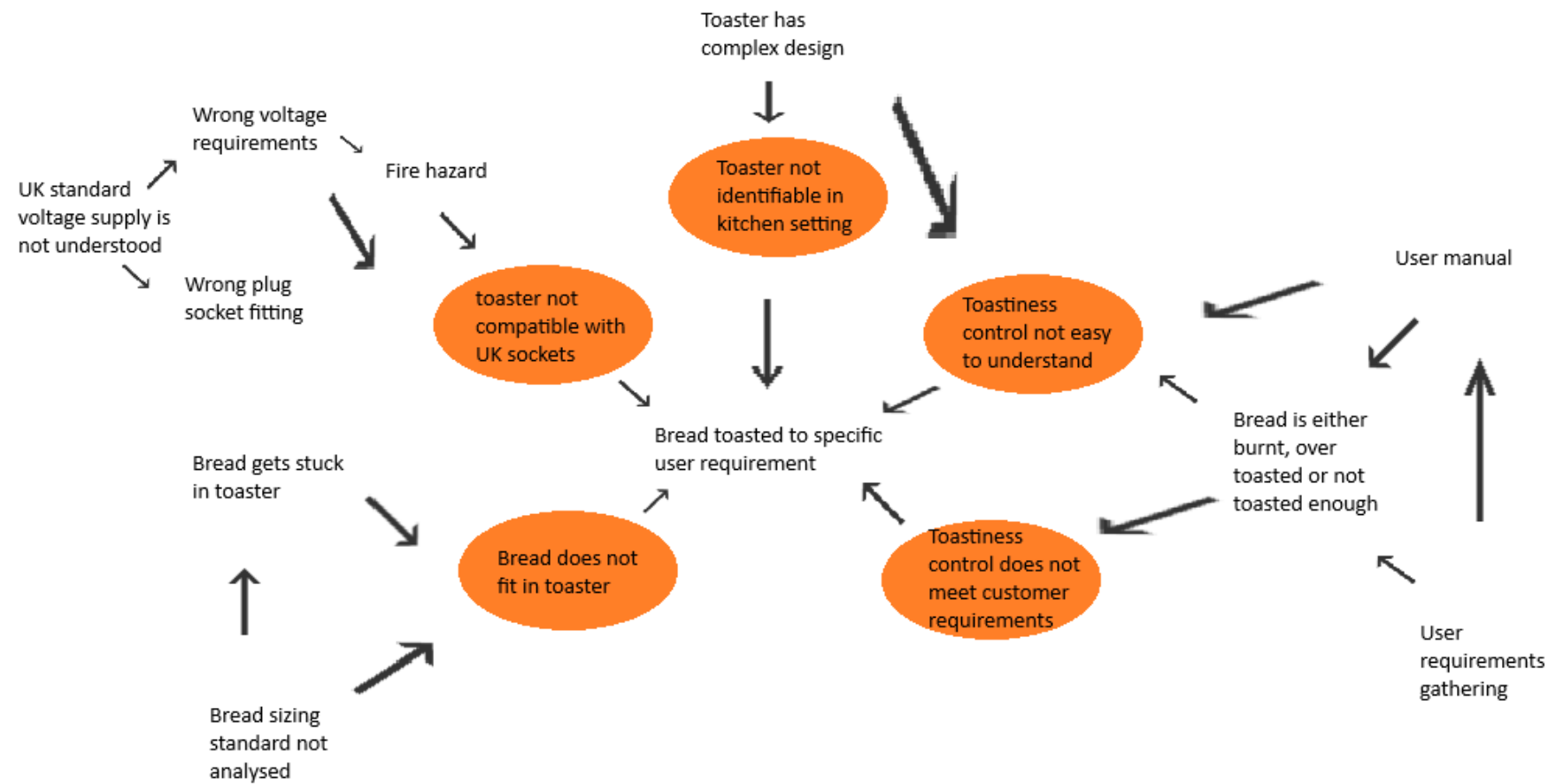


Figure 2 - Multiple-Cause Splash Diagram

9.4 Appendix 4 – Pairwise Comparison

		1	2	3	4	5	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	The toaster must be compatible with standard UK power supply	The toaster should be easy to identify in a kitchen setting	The control of toastiness must be intuitive	It should be easy to adjust the settings	The bread must be of a suitable thickness	Row Product	nth root of row product	Total Normalised
1	The toaster must be compatible with standard UK power supply	1	9	9	9	9	6561	6	65.51
2	The toaster should be easy to identify in a kitchen setting	0.11	1	0.5	0.2	0.2	0.0022	0	3.32
3	The control of toastiness must be intuitive	0.11	5	1	5	1	2.75	1	13.82
4	It should be easy to adjust the settings	0.11	5	0.2	1	0.5	0.055	1	6.32
5	The bread must be of a suitable thickness	0.11	4	1	2	1	0.88	1	11.01

Table 3 - Pairwise Comparison of Critical System Requirements

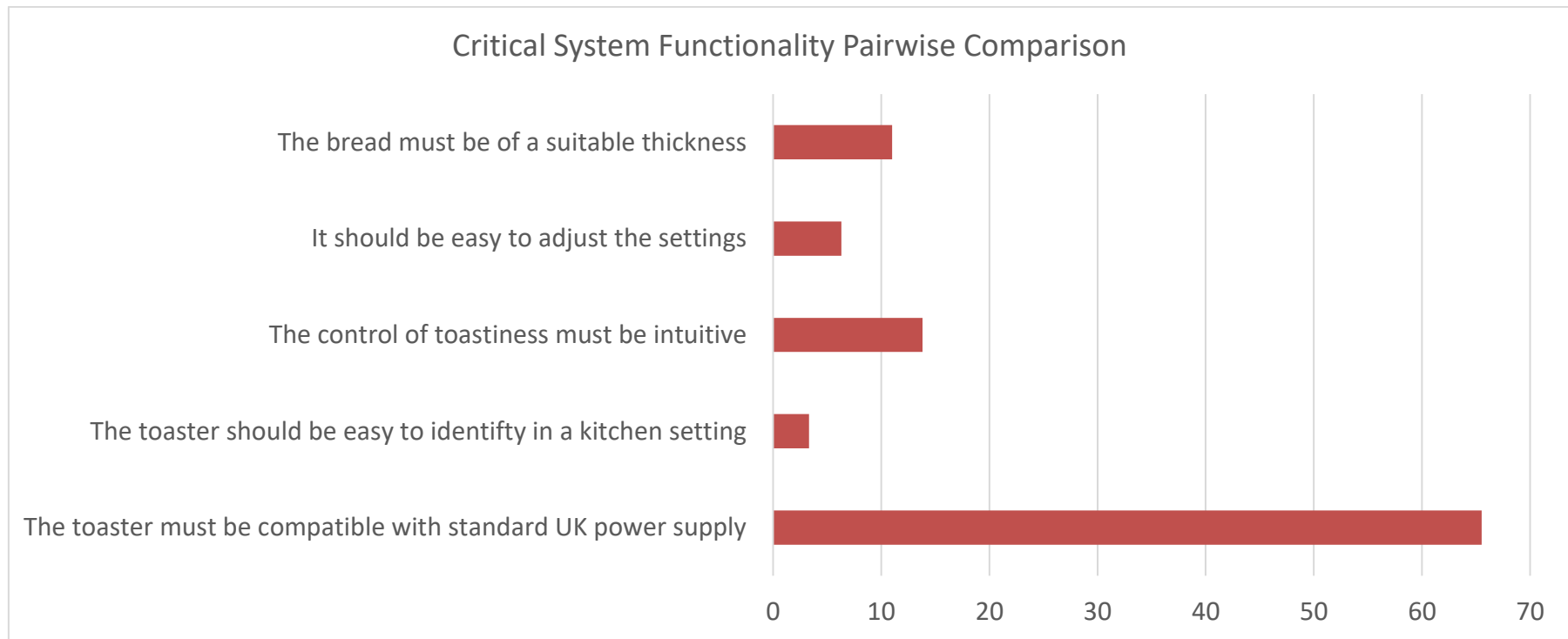


Figure 3 - Pairwise Comparison Graph

9.5 Appendix 5 – Design Quality Function Deployment 1

How	Importance	Bread acquired from supplier	Bread placed in toaster	Toaster lever pushed down and automatically locked into place	Setting set, setting returns to unset after use	Heating element engages	Once setting has been satisfied by the toaster, toaster disengages heating element and toaster lever unlocks, springing toasted bread upwards	Toasted bread is removed and used in desired manner
Requirements								
The toaster must be compatible with standard UK power supply	65.5	0	0	0	1	9	9	0
The toaster should be easy to identify in a kitchen setting	3.32	0	0	9	3	0	0	9
The control of toastiness must be intuitive	13.8	0	3	9	9	3	9	3
It should be easy to adjust the settings	6.32	0	1	3	9	3	9	1
The bread must be of a suitable thickness	11	9	9	0	0	0	0	1
Importance rating of process		99	147	173	257	650	771	89

Table 4 – QFD 1

9.6 Appendix 6 – Concept Design Mock-Ups

Twist-Knob Timer Design

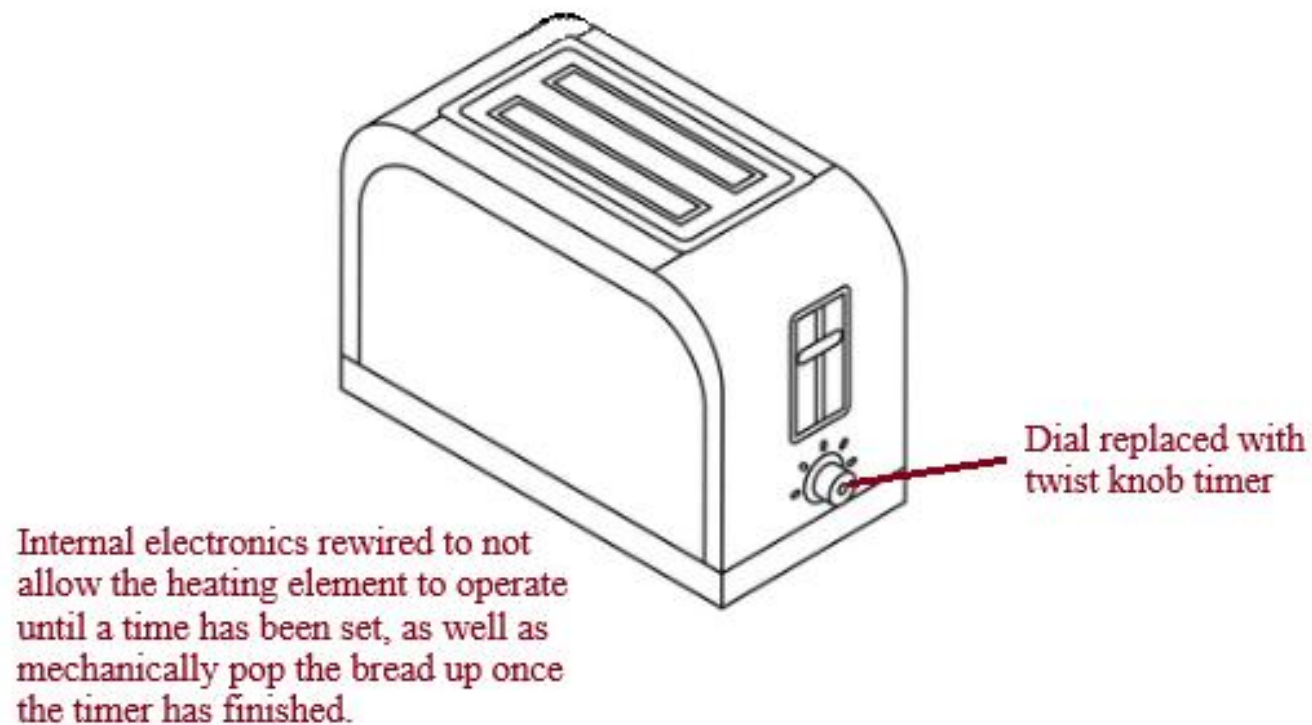


Figure 4 - Twist-Knob Timer Design

Digital Timer and Touch Screen Interface

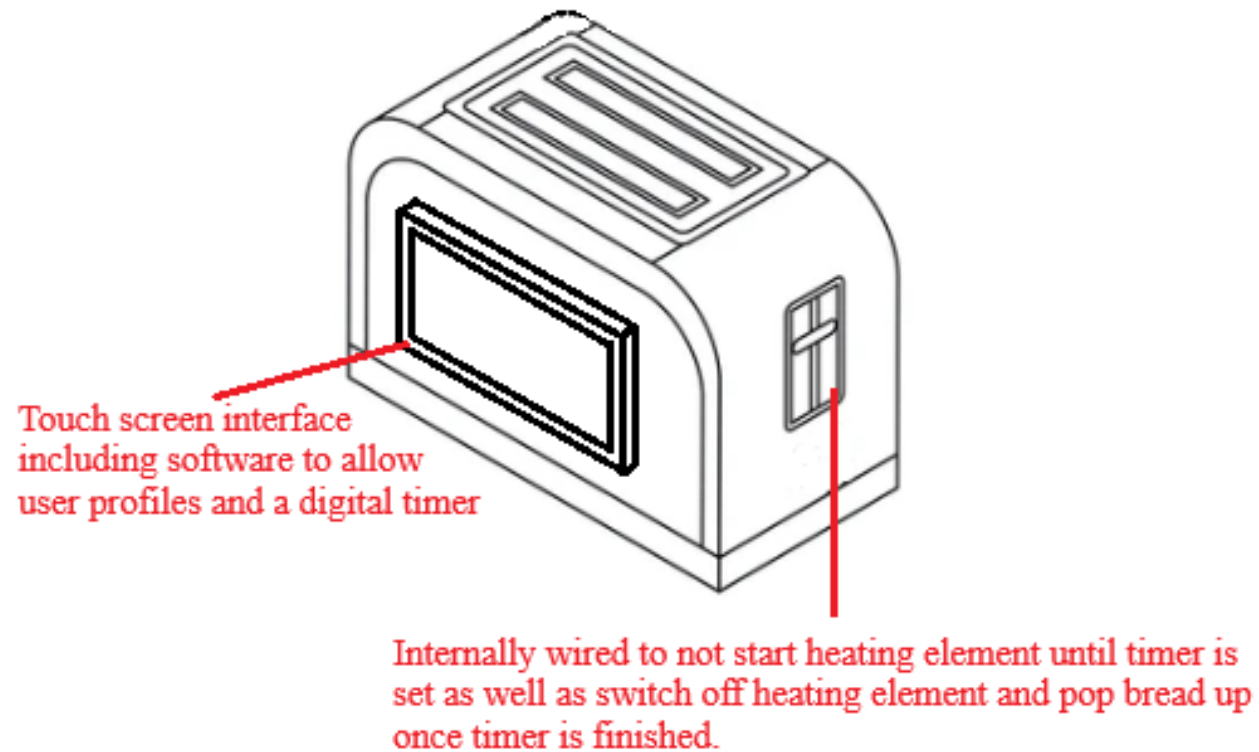


Figure 5 - Digital Timer Design

Optical Sensor and Touch Screen Interface

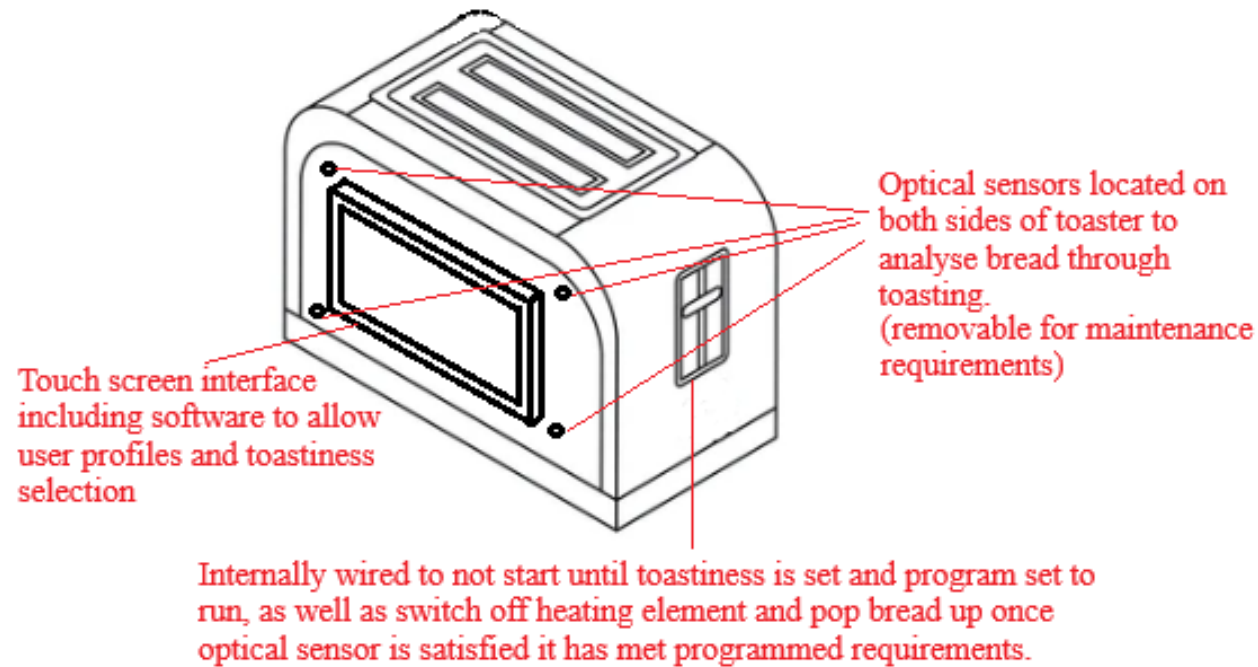


Figure 6 - Optical Sensor Design

9.7 Appendix 7 – System Pugh

	Relative Importance Equal	Relative importance Weighted	Standard Toaster	Twist knob timer	Digital timer	Optical sensor
WHATs - Customer Requirements						
The toaster must be compatible with standard UK power supply	1	65.51		0	0	0
The toaster should be easy to identify in a kitchen setting	1	3.322		0	0	0
The control of toastiness must be intuitive	1	13.83		2	2	1
It should be easy to adjust the settings	1	6.324		-1	2	1
The bread must be of a suitable thickness	1	11.01		0	0	0
Cumulative Score			0	1	4	2
Rating			0	21.3344	40.3071	20.1536
Ranking		100	0	- 20.3344	- 36.3071	- 18.1536

Table 5 - System Pugh

9.8 Appendix 8 – Design Functional Failure Mode Effect Analysis

Function	Failure Mode	System effect	Effect Seen by user	Severity	Cause	Mechanism (If Known)	Occurrence	Detection / prevention method	Detectability	Rating
The toaster must be compatible with standard UK power supply	too much supply voltage	Toaster will get too hot or short circuit, and potentially cause a fire	smoke, burning, fire	10	Internal transformer	Transformer not operating as required	1	heat cut out fuse	2	20
	too little supply voltage	Toaster will not operate effectively, undertoasting bread.	lack of toasted bread	3	Internal transformer	Transformer not operating as required	3	Voltage limit solenoid/transistor	2	18
	No supply voltage	Toaster will not operate	nothing will happen	1	short circuit/broken line	Circuitry/wiring defect	2	Power light indicates supply	2	4
	Intermittent supply voltage	Toaster will toast bread unevenly	undesired toastiness	3	arcing/bridging between connectors/grounding out	Circuitry/wiring defect	2	ground detection cut out fuse	2	12
	Unintended supply voltage	Toaster may heat up when not in use	user may burn fingers/hands when manipulating toaster	6	switch/solenoid closing when not in use	faulty component	1	Quality assurance on components prior to installation	3	18
The toaster should be easy to identify in a kitchen setting	too much - extravagantly designed	Toaster does not look like toaster	User cannot identify toaster	2	Design	N/A	7	User acceptance on design	2	28
	too little - minimalistically designed	Toaster is oversimplified, controls cannot be found	User cannot use toaster effectively	1	Design	N/A	6	User acceptance on design	2	12
	None - unable to identify	Toaster does not look like toaster	User cannot identify toaster	2	Design	N/A	10	User acceptance on design	2	40
	Intermittent - some people could identify	Toaster partially recognisable	Some users can identify and use toaster, some could not.	2	Design	N/A	5	User acceptance on design	2	20
	Unintended - designed similarly to another product and therefore mistaken	Toaster may look like another item	Users mistake toaster for an object with another function	3	Design	N/A	7	User acceptance on design	2	42
It should be easy to adjust the settings, to satisfy user requirements	too much - too many graduations or settings	Overcomplicates controls	User may not understand how to produce requirement	2	Control system	Control system	8	User test and trialling phase	2	32
	too little - vast differences between minor changes	Settings not easily adjusted	User may produce wrong requirement	2	Control system	Control system	7	User test and trialling phase	2	28
	None - only one setting	Only produces one user requirement	No user requirement met	2	Control system	Control system	9	Design as per user requirements	3	54
	Intermittent - graduations between settings are uneven	Difficult to set/control	User may produce wrong requirement	2	Control system	Control system	8	Quality assurance on even graduations and outputs	4	64
	Unintended - easily select the wrong setting	Produces incorrect requirement	User may produce wrong requirement	2	Control system	Control system	7	User test and trialling phase	2	28
The improved control of toastiness must be intuitive to use to prevent user error	too much - complex control, hard to comprehend	wrong setting may be chosen	user may use toaster incorrectly to requirements	2	Too many settings	Interface	7	User test and trialling phase	2	28
	too little - not enough guidance on control	wrong setting may be chosen	user may not be able to use toaster at all	2	Lack of use instructions	Instructions	6	User test and trialling phase	2	24
	None - user cannot understand controls	wrong setting may be chosen	user would not use toaster	2	Lack of use instructions/complex interface	Instructions and interface	10	User test and trialling phase	2	40
	Intermittent - some controls are understandable, others are not	wrong setting may be chosen	user may use toaster incorrectly to requirements	2	Complex interface	Interface	5	User test and trialling phase	2	20
	Unintended - some controls provide functions which are unintended	wrong setting may be chosen	user may use toaster incorrectly to requirements	2	Complex interface	Interface	5	User test and trialling phase	2	20
The bread must be of a suitable thickness for use in toaster	too much - bread will not fit	unusable	bread unable to be toasted	2	Material supply	Supplier	10	Quality assurance on supply from supplier/change supplier if required	5	100
	too little -bread too thin	bread may burn	bread is overtoasted	2	Material supply	Supplier	7	Quality assurance on supply from supplier/change supplier if required	5	70
	None - no bread	no toast produced	no bread to toast	2	Material supply	Supplier	10	Ensure supplier can supply/change supplier if required	5	100
	Intermittent - uneven bread thickness	bread does not toast consistently	toaster burns some slices whilst undertoasts others	2	Material supply	Supplier	7	Quality assurance on supply from supplier/change supplier if required	5	70
	Unintended - bread partially fits	bread may have part of it hanging out.	toaster only toasts part or the bread	2	Material supply	Supplier	8	Quality assurance on supply from supplier/change supplier if required	5	80

Table 6 - DFMEA

9.9 Appendix 9 – Quality Function Deployment 2

Design feature	Importance		Importance	A digital timer for highly accurate timing when setting a program on the toaster	A touch screen interface to allow clarity of time remaining, user setting visibility and user profile setup	An internal program function which prevents the user from toasting without setting the program first
Function Process						
Bread acquired from supplier	99	10	10	0	0	0
Bread placed in toaster	147	10	15	0	0	0
Toaster lever pushed down and automatically locked into place	173	10	17	1	9	3
Program set, setting returns to unset after use	257	10	26	9	9	9
Heating element engages	650	10	65	1	3	9
Once setting has been satisfied by the toaster, toaster disengages heating element and toaster lever unlocks, springing toasted bread upwards	771	10	77	9	9	1
Toasted bread is removed and used in desired manner	89	10	9	1	3	1
Priority score				1016	1303	954

Table 7 - QFD 2