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Systems Engineering Report

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Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct

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List of Abbreviations

NFR – Non-Functional Performance Requirement

1. Introduction

1.1.1. Systems Engineering and the Systems Engineering Rationale

Before the widespread use of Systems Engineering, the development process was messy and focused on a pre-determined idea of what the solution to a problem may be which introduced a lot of rework and adjustments leading to long development times.

Systems Engineering is the approach of solving an engineering problem as a requirement driven exercise rather than solution driven. It looks at the system as a whole rather than the individual components. This helps to ensure the requirements of the various stakeholders are met.

1.1.2. Diagramming

Since systems engineering deals with the system as a whole, it is important to carry out diagramming in order to ensure all of the thoughts are captured. A multiple cause diagram is an example of this whereby your intended outcome can become the core of the diagram and branches can be made from that which dive deeper into causation required in order to achieve that outcome. When producing one, it is still important to think of some customer requirements which will always be present like the safety of the system. This should also be expanded on once the requirements have been collected and prioritised to allow for clearer depictions of the thought process.

This process falls under convergent thinking, which is where the ideas surrounding the resolution of the engineering problem and how it is achieved become linked. To put this idea in the context of the toaster, an example of a multiple cause diagram is below.

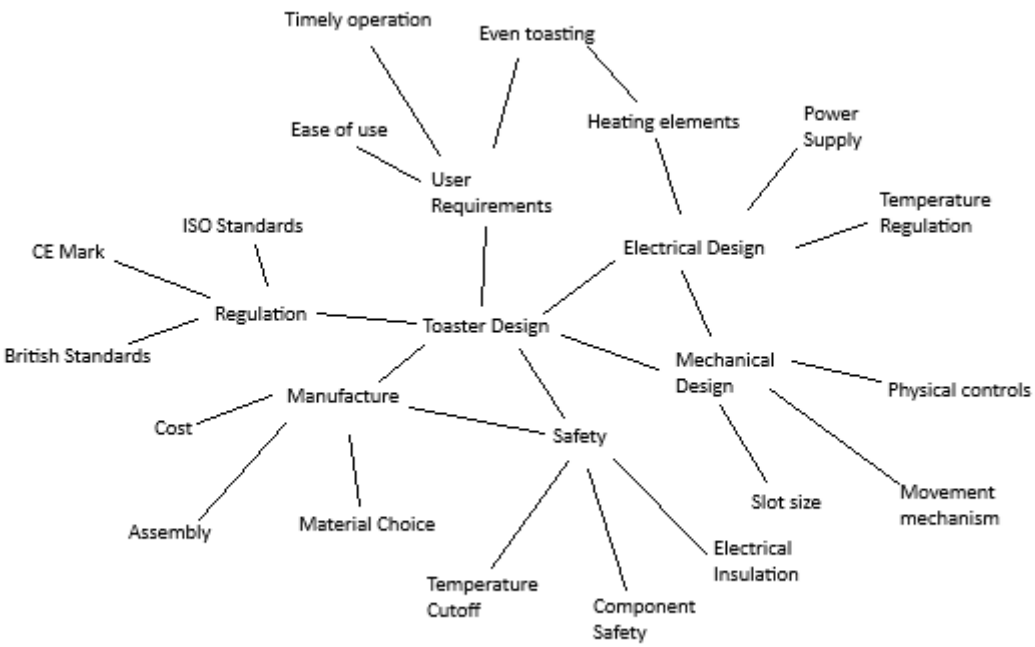

Figure 1 – Multiple Cause Diagram for Electric Toaster

2. Generation of System Requirements

When developing a system it is important to collect/generate requirements from as many associated stakeholders as possible to ensure that the needs of the user group are met. This helps to ensure that the right product or system is produced and that it is able to perform the actions required in a way that is accepted. The requirements will be converted into metrics that the system can be tested against.

2.1.1. Types of requirements

A requirement in the context of systems engineering is a testable statement which define what the system or solution must do or how it must do it.

Functional Requirements (FR) – Details what the system must achieve without restricting the design of the solution (how it meets the requirements). They can be directly linked to the needs of the operator/customer through usability, safety and consistency. An example of an FR would be 'The toaster must be capable of heating an item'

Non-Functional Performance Requirements (NFR) – Provides constrictive metrics that the system must achieve. These detail 'how well' a concept or solution must perform, an example of an NFR would be 'The toaster shall have a time limit of 5 minutes of toasting before a safety shut off'.

Non-Functional Implementation Requirements (NFIR) – Details how the system must be built or implemented. They are requirements which focus specifically on providing constraints to the design or development of the system. An example of an NFIR would be 'The system will be operated using a 240V supply of power from the UK three-pin plug'.

Non-Functional System Requirements (NFSR) – Details how well the system must perform under specified conditions. They are measurable and testable requirements which apply system wide. An example of an NFSR would be 'The toaster must perform during operating conditions of -5°C to 40°C'.

2.1.2. Identification of Subsystems

2.1.3. Use Case for electric toaster

A Use Case is a breakdown of the operations and cycles which take place whilst the system is in use.

Goal

Caramelise bread surface to selected level by user.

Actors

- Operator.
- Internal timing/control mechanism.
- Toaster power supply.

Pre-conditions

- Toaster provided with reliable and functioning electric power source.
- Toaster is idle and safe to operate.
- Item to be toasted is present and fits within the slot.

Post-conditions

- Item to be toasted has browned to desired level.
- Toasted item delivered to accessible location.
- Toaster has identified operator of it's cycle completion.

Basic Flow (Success Flow)

Step 1: Operator places item to be toasted within slot.

Step 2: Operator determines and sets appropriate level of browning.

Step 3: Item to be toasted is positioned appropriately.

Step 4: Operator starts the toasting process/cycle.

Step 5: Heating elements powered.

Step 6: Item to be toasted kept within heated area until determined browning has completed.

Step 7: Determination of browning level achieved.

Step 8: Heating elements removed from power.

Step 9: Toaster positions bread in a safe to access location.

Step 10: Toaster generates indication the cycle has completed.

Alternative Flows

A1: Operator cancels operation of toaster

- Can occur during steps 4-7, operator cancels toasters operation.
- Toaster halts ensuring heating elements are not powered and the bread is positioned

A2: Power outage

- Can occur during any step of basic flow.
- All operation is disabled, heating elements unpowered.
- Toaster ensures a safe state once power is restored.

Exception Flows

E1: Toaster unpowered (not connected to power source)

- Can occur during step 3, operator starts the toasting process.
- Toaster does not start the cycle, heating elements still unpowered and in safe idle state.

Outcome

- No response from toaster to operator input.

E2: Temperature of system exceeds safe limits

- Can occur during steps 4-7, user cancels toasters operation.
- Toaster halts ensuring heating elements are not powered and returns to safe position

Outcome

- Incomplete browning.

2.1.4. Electric Toaster V-Diagram

V-Diagrams are used within systems engineering to ensure traceability from the requirements through to the testing of the completed system. This is achieved by detailing what is required, into how the system is constructed/built, into how the system is tested at each level of detail.

The benefits of using V-Diagrams is that at each stage the testing/verification for those requirements can be determined. This starts at the overall system level progressing towards the component level for the system ensuring that you have a complete understanding of what needs to be tested. V-Diagrams also support development through the reduction of risk and therefore cost to the project through providing fewer misunderstandings between stakeholders as well as reducing the likelihood of reworks through the earlier detection of compliance issues with the requirements.

The V-Diagram (text form) for this electric toaster would look like the following:

- User/Market Requirements – What the user needs
- System Requirements – What the toaster must do
- Subsystem Requirements – HEATING, CONTROL, SAFETY
- Component Design/Implementation – PCB, Case, Sensors, Heating Elements
- BUILD / ASSEMBLY of toaster – Bottom of ‘V’
- Component Verification – Component reliability
- Subsystem Verification – HEATING, CONTROL, SAFETY
- System Validation – Full-system testing of toaster, end-to-end testing
- User Acceptance Testing – Does the toaster perform according to the user?

2.2. Required Functionality

From Use Case

- RECEIVE POWER – Is able to receive electricity in order to power the system.
- IDENTIFY INTENT – Determine the level of browning required by the operator.
- TRANSFER SIGNAL – Provide a bridge between the user inputs and the control mechanism of the toaster.
- MANOEUVRE ITEM – Position toasting item correctly for even heating.
- PROVIDE HEATING – Toasting of the item to the desired browning level.
- REGULATE HEAT – Ensures predictability in timing for browning.
- TERMINATE HEATING – Stop heating during faults, cancellation or completion of cycle.
- CANCEL CYCLE – Operator able to cancel toasting cycle during the main operation.
- IDENTIFY BROWNING – Determine when the desired level of browning has been achieved.
- FINISH SAFELY – Completion of cycle has minimal risk to operator.

2.3. Determination of requirements

When determining requirements it is important to take into consideration the different stakeholders and bodies that are involved within the development and use of the system. These can be both internal (operator/customers) or external (legislative bodies). The requirements of these stakeholders will differ and prioritisation of these requirements is important to ensure that the needs can be met.

From Use Case

Functional Requirements

- The operator requires that the toaster is able to receive instruction
- The operator requires that the toaster is safe to operate
- The operator requires that the toaster browns bread evenly
- The operator requires that the time taken to complete a cycle is appropriate.
- The operator requires that the input for the toaster is able to receive bread slices and other ‘toastable’ articles.

From Legislation

Functional Requirements

- The law requires that the toaster is designed to be protected against overheating.
- The law requires that the toaster is designed to be protected against insulation failure.
- The law requires the restriction of lead and other hazardous substances in electrical and electronic equipment.

Not Functional Requirements

- The law requires that the toaster is designed for use at UK typical voltages (230V).
- The law requires that the plug socket used is the standard 3 pin UK plug socket.

3. Requirements Prioritisation

One of the techniques used within systems engineering for requirements prioritisation is the MoSCoW method. This is split into, Must have, Should have, Could have and Won't have. These differing tiers represent a level of priority for the requirements. A description of each is as follows:

- Must have: These are critical requirements essential for the projects success. [1]
- Should have: These are important but not critical features. They are high-priority but less time-sensitive than "Must have" items. [1]
- Could have: These are desirable features that can be included if time and resources allow but do not impact the project's success if omitted. [1]
- Won't have: These are the lowest-priority features, agreed to be excluded from the current delivery cycle but may be considered for future iterations. [1]

For the purpose of the assignment, the number of requirements being brought into further analysis has been capped to 5.

MoSCoW Assignments of electric toaster requirements:

Must Have

- The toaster must be able to receive instruction from an operator.
- The toaster must be safe to operated.
- The toaster must conform to BS and ISO standards.

Should Have

- The toaster should allow the toasting level to be changed.
- The toaster should evenly toast the surface of the articles.
- The toaster should be identifiable.

Could Have

- The toaster could include a defrost mode.
- The toaster could include a reheat mode.
- The toaster could include a touchscreen.

Won't Have

- The toaster won't have Bluetooth control.
- The toaster won't have automatic loading of bread.
- The toaster won't have 'smart home' integration.

The following requirements were chosen to continue to requirement analysis and importance:

- The toaster must be able to receive instruction from an operator.
- The toaster must be safe to operate.
- The toaster must conform to BS and ISO standards.
- The toaster should allow the toasting level to be changed.
- The toaster should evenly toast the surface of the articles.

3.1. Pairwise Comparison of requirements

	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 toaster must be able to receive instruction from an operator.	2 The toaster must be safe to operate.	3 The toaster must conform to BS and ISO standards.	4 The toaster should allow the toasting level to be changed.	5 The toaster should evenly toast the surface of the articles.	Calc Row Product	nth root of row product	Calc Total Normalised
1	The toaster must be able to receive instruction from an operator.	1	0.5	1	5	2	5	1.38	23.4
2	The toaster must be safe to operate.	2	1	1	2	5	20	1.821	30.8
3	The toaster must conform to BS and ISO standards.	1	1	1	2	2	4	1.32	22.3
4	The toaster should allow the toasting level to be changed.	0.2	0.5	0.5	1	1	0.05	0.549	9.3
5	The toaster should evenly toast the surface of the articles.	0.5	0.2	0.5	1	1	0.05	0.838	14.2
							29.1	5.90752	100

Figure 2 – Pairwise comparison of main requirements

Pairwise comparison within systems engineering is used to determine relationships between the requirements. The values place within the table show the preferential importance between the two requirements. The requirements in the horizontal position are compared to the requirements in the vertical orientation whereby the value is the horizontal requirements importance in comparison to the one vertical from that cell. In this example of its use, the three primary requirements have been determined to be receiving instruction, safety of operation and the conformance to standards.

Pairwise diagramming reduces the cognitive load when assessing requirements by repeating comparisons between two requirements instead of pooling them together which can add unnecessary complexity. This diagram also acts as another record of the thought process and can be reviewed more easily with stakeholders since the interpretation of the relationships is clearly shown. This can be especially beneficial where a decision includes qualitative factors where subjectivity is involved.

3.1.1. Functional Importance (QFD 1)

How	Importance	RECIEVE POWER	IDENTIFY INTENT	TRANSFER SIGNAL	MANOEUVRE ITEM	PROVIDE HEATING	REGULATE HEAT	TERMINATE HEATING	CANCEL CYCLE	IDENTIFY BROWNING	FINISH SAFELY
Requirements											
The toaster must be able to receive instruction from an operator.	23.36	3	9	9	1	3	1	3	9	3	9
The toaster must be safe to operate.	30.82	3	3	3	1	1	9	1	9	1	9
The toaster must conform to BS and ISO standards.	22.34	9	3	3	3	3	9	3	3	3	9
The toaster should allow the toasting level to be changed.	9.30	3	9	9	1	3	3	3	3	9	3
The toaster should evenly toast the surface of the articles.	14.19	3	1	1	3	9	9	3	3	9	3
	100	21	25	25	9	19	31	13	27	25	33
Target											
Benchmark											
Ideal Value											
How Much??? Derive target values for each function. This will determine how well the existing design performs and how well our modified version will perform											

Figure 3 – Functional Importance Matrix (QFD 1)

When producing a Quality Function Deployment 1 (QFD 1), the identified requirements are prioritised through deriving their relation to the key functions. The requirements are either graded 1, 3, or 9 depending on the strength of the link. For example, 'The toaster must be able to receive instruction from an operator' was graded a 9 against IDENTIFY INTENT as a function due to the critical relationship between them.

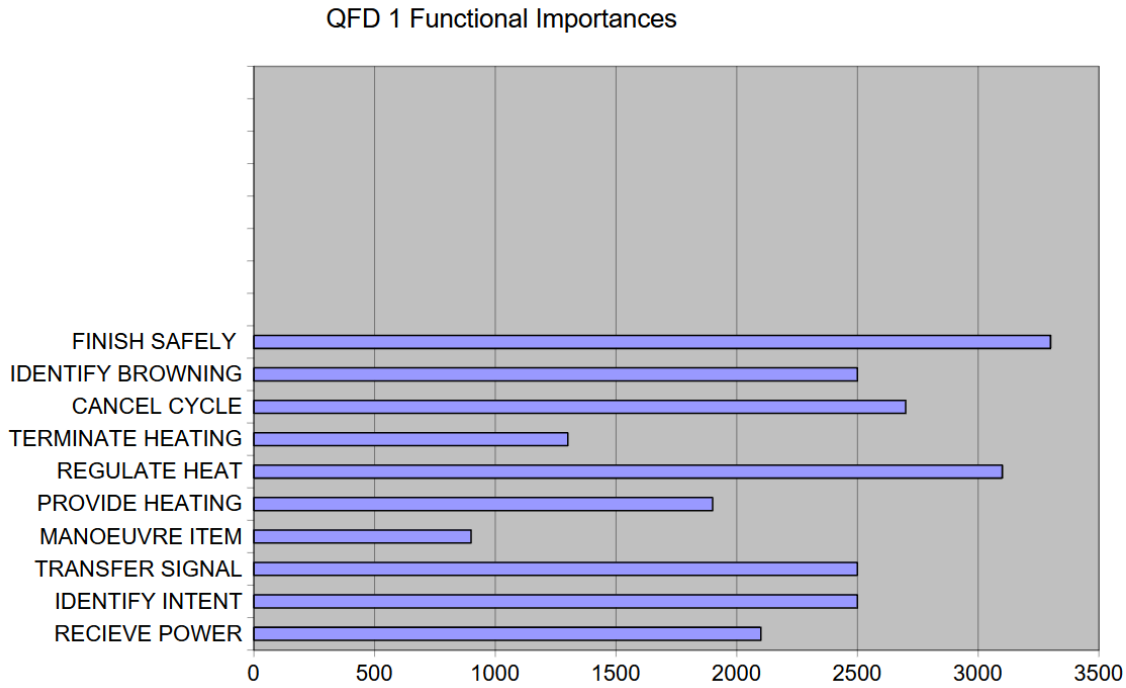

Figure 3 – Functional Importance Matrix (QFD 1)

3.1.2. Component Criticality (QFD 2)

In order to identify the importance of each of the basic functions of the design, a QFD 2 is produced. In this matrix the basic functions are scored against each step of the success flow within the use case. This provides a clear picture on the use of these functions and will identify a level of priority for each of them in

terms of their criticality to the success of that cycle. Like QFD 1, the scores are graded 1, 3, and 9.

Design feature	Importance		Importance	Step 1: Operator places item to be toasted within slot.	Step 2: Operator determines and sets appropriate level of browning.	Step 3: Item to be toasted is positioned appropriately.	Step 4: Operator starts the toasting process/cycle.	Step 5: Heating elements powered.	Step 6: Item to be toasted kept within heated area until determined browning has completed.	Step 7: Determination of browning level achieved.	Step 8: Heating elements removed from power.	Step 9: Toaster positions bread in a safe to access location.	Step 10: Toaster generates indication the cycle has completed.
Functionality													
RECEIVE POWER	2100	10	210	1	3	3	3	9	9	9	3	3	3
IDENTIFY INTENT	2500	10	250	3	9	3	9	1	9	3	1	3	3
TRANSFER SIGNAL	2500	10	90	1	9	3	3	1	3	3	3	3	9
MANOEUVRE ITEM	900	10	190	9	1	9	3	1	1	1	1	9	1
PROVIDE HEATING	1900	10	310	1	1	1	3	9	9	3	9	1	1
REGULATE HEAT	3100	10	130	1	1	1	3	9	9	3	9	1	1
TERMINATE HEATING	1300	10	270	1	9	1	1	3	3	9	3	1	1
CANCEL CYCLE	2700	10	250	1	9	1	1	1	1	9	3	1	1
IDENTIFY BROWNING	2500	10	330	1	3	1	1	1	9	9	1	1	1
FINISH SAFELY	3300	10	330	3	3	3	9	9	9	9	9	3	3
				5040	10980	5640	8860	10740	15560	15040	10160	5640	4660

Figure 3 – Function Criticality Matrix (QFD 1)

4. Concept generation

Now that the requirements and functionalities have been prioritised it is appropriate to generate multiple concepts to be assessed. To start this process, a Functional Means Analysis matrix can be completed. This details each of the functions and provides a space for recommendation on subsystems to meet that function. From these suggestions, 3 concepts for further evaluation can be produced.

4.1.1. Functional Means Analysis

A Function Means Analysis is a tool for generating and capturing the ideas surrounding concepts. This is a 4 stage process:

- Functionality is identified.
- Solutions for each function are generated.
- Determine the selection and de-selection criteria.
- Review remaining options to generate system size concepts.

For this toaster example, below is a completed FMA:

Function	Means						Key	
RECEIVE POWER	UK 3 Pin	Battery	Wireless Power Delivery (EM)	Bicycle dynamo	Geothermal	Chemical		Safe to operate
IDENTIFY INTENT	Touchscreen	Buttons	Dials	Potentiometer bars				Receive instruction
TRANSFER SIGNAL	Wires	Wireless	Physical mechanism	Voice				Conformation to BS standards
MANOEUVRE ITEM	Slot	Conveyor	Transfer plate	Operator retention of item	Sliding tray			Adjustment of toasting level
PROVIDE HEATING	Directed heating elements	Fanned heating elements	Open flame	Gas heating	Chemical heating	Radiation Heating		Even toasting
REGULATE HEAT	Thermometers	PID controllers	Operator regulated	Timer	Optical sensor	Variable heating elements		
TERMINATE HEATING	Switches	Power shutoff	Bread lift using spring mechanism					
CANCEL CYCLE	Ejection springs	Power shutoff	Operator removes toast	Insulate bread from heat source				
IDENTIFY BROWNING	Thermometers	PID controllers	Operator regulated	Timer	Optical sensor	Fuzzy logic		
FINISH SAFELY	Insulation	Flammability						

Figure 4 – Function Means Analysis

In this matrix, the coloured in cells have been discredited due to their weakness to follow the associated key requirement of that colour. This allows for a clear record of the decisions made when generating the concepts for the system.

From this, the chosen concepts to assess are:

Concept 1

- UK 3-pin power delivery – Standard to toasters on the market.
- Touchscreen display – Modernisation attempt at the interface between the operator and the machines
- Slot – Rectangle slots in top of toaster.

- Electric heating elements – Provably safe and already in use with toasters on the market.
- Inbuilt PID controller – PID Controller accurately maintains a determined temperature, to be tested, which is ideal for toasting bread. This has potential to be changed through a setting on the touchscreen increasing the capability of the toaster.
- Switch – Circuit to heating elements broken on completion/cancellation.

Concept 2

- Wireless power delivery – Placed on charging pad to deliver power to the toaster.
- Simple button controls – Simplification of controls to increase the toasters accessibility.
- Conveyor – Conveyor system to allow a larger volume of bread.
- Fanned electric heating elements – Typically used in air fryers.
- Fuzzy logic – Toaster uses algorithms to determine when bread has been toasted to set level.
- Switch – Circuit to heating elements broken on completion/cancellation.

Concept 3

- UK 3-pin power delivery – Standard to toasters on the market.
- Gas heating – Gas heating elements.
- Dials – Circular dials to determine temperature and duration for toasting time.
- Slot – Rectangle slots in top of toaster.
- Thermometer – Thermometer temperature controls which activate after temperature has dropped below threshold.
- Power shut-off – Toaster shuts off power to self once toasting cycle is completed.

4.1.2. System Pugh Diagramming

Pugh diagramming is used within Systems Engineering to determine a likely winning concept before testing. This is achieved through a comparison of the prioritised requirements against each of the concepts determined through the Functional Means Analysis. The grades 9, 3 and 1 are again used in order to assign how strongly that concept has ‘achieved’ this criteria however they are also affected by a predetermined multiplier for each requirement. This then generates a final concept for the toaster in order to be tested.

	Relative Importance Equal	Relative importance Weighted	Concept 1	Concept 2	Concept 3
WHATs - Customer Requirements					
The toaster must be able to receive instruction from an operator.	5	23.355	9	3	3
The toaster must be safe to operate.	5	30.818	3	3	9
The toaster must conform to BS and ISO standards.	5	23.355	3	3	1
The toaster should allow the toasting level to be changed.	5	30.818	9	3	9
The toaster should evenly toast the surface of the articles.	5	22.336	3	3	3
Ranking	100		**135**	**75**	**125**

Figure 5 – Pugh Diagram

In this example, concept 1 was determined to be the strongest concept to be taken forward for the next stages of development. All of the requirements were set to a multiplier of 5 due to their criticality in the success of the toaster.

5. References

[1] M. H. Keshavarz and T. M. Klapötke, "A novel method for prediction of the critical diameter of solid pure and composite high explosives to assess their explosion safety in an industrial setting," J. Energ. Mater., vol. 37, no. 3, pp. 331-339, 2019, doi: 10.1080/07370652.2019.1610878.