

Ordnance Munitions and Explosives Apprenticeship (BEng)

Level 5 Systems Engineering ACDA5021

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Introduction

System engineering encompasses multiple disciplines with the aim to incorporate complex individual elements into a single system to achieve a desired goal. It integrates various engineering disciplines and speciality sections into one holistic approach, producing a structured development process that starts at the concept phase and continues through to the item in question being used. By using this approach to manage the complexity of modern systems it ensures all areas of a project are taken into consideration and are integrated into a solution [1].

System engineering is crucial to aid in the design and manufacturing of complex systems, it ensures all aspects of a system work together, meeting the desired performance requirements, cost, and timescales. The holistic approach helps to identify potential issues early in the project's lifecycle reducing the risk and improving the quality of the final product. As part of the design and manufacturing, system engineering facilitates the integration of all the subsystems ensuring they meet the requirements and perform as expected in the larger system [1].

This assignment's aim is to explore the key principles and practices of system engineering primarily in the application of design and manufacturing, with the use of a case study as the backbone of the assignment. The case study will be used to demonstrate the methodologies and tools used in system engineering to aid with implementing a real-world project from requirements setting, to design concept and manufacturing. Using a dedicated system engineering approach to set the requirements for the project and analysing their importance against each other. Establishing the functional output of the requirements set as well as Quality Function Deployment (QFD) 1 and 2, used to establish a way forward by converting the requirements into engineering specifications and plans to carry the project forward [2]. The case study will provide a comprehensive understanding to the value of system engineering in design and manufacturing of a system.

Case Study Description

The case study will be based around the need for a replacement and upgrade of a garden shed. The current shed is old, falling apart and is no longer providing a solid and secure storage for any of the high value items such as mountain bikes and specialist tools contained within it. It is also no longer weatherproof which is contributing to the deterioration of some of the items inside from a damp environment leading to the formation of mold and rust.

Although a shed replacement would not typically be considered a system it still has all the hallmarks of a system, with different requirements, limitations and does contain small areas that contribute to a larger system. For example, a typical shed consists of a structural building, some form of entrance and also the possibility of including an electrical system inside as well. They all require different parameters to be met and to contribute to the overall system of the shed. To add to the system engineering approach the purpose of the shed will have an additional aspect added at the requirements stage, that a typical shed would not usually consist of. The solution will also have to accommodate the use of a small

workshop along with the ability to be used for storage, adding to the complexity of the case study.

The approach to choosing an appropriate replacement for the current shed can be undertaken using a typical system engineering approach by defining the requirements set as provided by the end user. Then undertaking a comparison between the requirements to determine the priority order and also conducting a requirement functionality analysis. Which is then followed by the QFD1 eventually leading to a design QFD2. The two QFD stages will be used to help determine a functional and feature importance level which in turn helps steer the design of the solution to a suitable outcome.

Methodology

The methodology used within this case study follows a typical Quality Function Deployment (QFD) approach to transfer customer needs into a final product [3]. The initial phase of the project is to first identify key customer requirements needed to drive the project forward. Without these there is no basis to start the down select process. They aid in determining the task the system must undertake [4].

The requirements were then taken through QFD1 which is where the customer requirements are translated into measurable Technical Requirements [3]. This means the requirements set out by the customer can be attributed to a possible technical outcome, by doing this, QFD1 can be used to determine the relationship between the requirements and a possible solution [3]. This is then taken into QFD2 which is the translation of Technical Requirements into compliant Design Solution (down to individual parts or components) [3]. QFD2 is used to determine the solution to the requirements set out by the customer.

After the two previous QFD stages, the process typically follows on with QFD 3 and 4. Although these stages will not be covered by the case study it is still prudent to mention their importance within the holistic approach to system engineering. QFD 3 is used to translate the design solution requirements into realisation system requirements. This step identifies and provides the manufacturing solution to the requirements [3]. QFD 4 is used for the translation of realisation system requirements into a set of delivery requirements [3]. Essential determining the how much and how of the manufacturing.

Key Customer Requirements

The first stage of any project is to capture and understand the requirements, as they are an integral part of driving the projects direction. The requirements can typically be very vague and nontechnical in nature, as they are primarily concerned with what their desire is not how its achieved [3]. For example, some customer requirements could be based around the shape, comfortable and sounds good (if the requirements are based on a vehicle). Although these requirements are broad and vague they need to be recorded and used for the basis of the analysis.

There are various ways of going about requirements gathering and a good approach will use a combination of qualitative and quantitative methods. These can include questionnaires and

interviews with all the customer stakeholders, to gain a broad and varied set of requirements which ensures a well-rounded understanding of the customer needs.

It is beneficial to get the customer to assign an importance level to these requirements. By prioritising these requirements on a scale of 1 to 5, it helps ensure the most important requirement stated by the customer is met first giving greater value to the customer and allowing appropriate levels of attention to be allocated to these areas. Without this approach, time and effort could be wasted on less critical areas, which might lead to delays and cost overruns in the project. This approach could also help identify potential risks early in the project allowing the appropriate adjustment to be made [3].

These stages were undertaken as part of the case study within this assignment, the lead customer, secondary customer, and tertiary customer (also known as the Homeowner, long-haired general and Offspring) were all asked to name key requirements for the replacement shed and can be seen below in the below table:

Originator	Requirements
Homeowner	The homeowner requires the solution to fit on a concrete plinth already installed into the garden
Homeowner	The homeowner requires there to be suitable storage capacity to accommodate regular household items and garden tools
Homeowner	The homeowner requires there to be a suitable area to be used as a workshop for basic household maintenance/construction tasks
Homeowner	The homeowner requires the solution to be sturdy and solid construction
Homeowner	The homeowner requires the solution to be weather resistance to all UK weather conditions
Homeowner	The homeowner requires the solution to require minimum maintenance in its lifetime
Homeowner	The homeowner requires there to be electrical power outlets internally and externally to the solution
Homeowner	The homeowner requires there to be suitable lit though natural and electrical means
Long-haired general	The long-haired general requires there to be suitable space to store the seasonal hot tube when not in use
Long-haired general	The long-haired general requires there to be suitable location to mount a washing line to the external surface of the solution
Offspring	The offspring require suitable spare space to store their bikes

Table 1: Customer requirements

These requirements were then put through a pairwise comparison of requirement, this is a comparison technique where a relative importance is applied to the requirements by the customer against each requirement as pairs [5]. With the overall result used to identify the most important requirements as described in the paragraphs above.

		1	2	3	4	5	6	7	8	9	10	11	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 home owner requires the solution to fit on a concrete plinth already installed into the garden	The home owner requires there to be suitable storage capacity to accommodate regular house hold items and garden tools	The home owner requires there to be a suitable area to be used as a workshop for basic household maintenance/construction tasks	The home owner requires the solution to be sturdy and solid construction	The home owner requires the solution to be weather resistance to all UK weather conditions	The home owner requires the solution to require minimum maintenance in its life time	The home owner requires there to be electrical power outlets internally and externally to the solution	The home owner requires there to be suitable lit though natural and electrical means	The long haired general requires there to be suitable space to store the seasonal hot tube when not in use	The long haired general requires there to be suitable location to mount a washing line to the external surface of the solution	The off spring require suitable sprare space to store their bikes	Row Product	nth root of row product	Total Normalised
1	The home owner requires the solution to fit on a concrete plinth already installed into the garden	1	2	2	2	1	1	1	1	1	1	1	8	1	8.3
2	The home owner requires there to be suitable storage capacity to accommodate regular house hold items and garden tools	2	1	9	2	2	2	1	1	1	1	1	144	1	9.6
3	The home owner requires there to be a suitable area to be used as a workshop for basic household maintenance/construction tasks	2	9	1	2	2	2	5	5	1	1	1	3600	2	11
4	The home owner requires the solution to be sturdy and solid construction	2	2	2	1	2	5	2	2	1	1	1	320	1	10
5	The home owner requires the solution to be weather resistance to all UK weather conditions	1	2	2	2	1	5	2	2	1	1	1	160	1	9.6
6	The home owner requires the solution to require minimum maintenance in its life time	1	2	2	5	5	1	2	2	1	1	1	400	1	10
7	The home owner requires there to be electrical power outlets internally and externally to the solution	1	1	5	2	2	2	1	2	1	1	1	80	1	9.3
8	The home owner requires there to be suitable lit though natural and electrical means	1	1	5	2	2	2	2	1	1	1	1	80	1	9.3
9	The long haired general requires there to be suitable space to store the seasonal hot tube when not in use	1	1	1	1	1	1	1	1	1	1	1	1	1	7.5
10	The long haired general requires there to be suitable location to mount a washing line to the external surface of the solution	1	1	1	1	1	1	1	1	1	1	1	1	1	7.5
11	The off spring require suitable sprare space to store their bikes	1	1	1	1	1	1	1	1	1	1	1	1	1	7.5
													4795	13.36	100

Table 2: Pairwise comparison of requirements

Below in table 3 are the results from the comparison conducted in table 2. This allows for a clear picture of the most important requirements allowing for functional requirements to be determined.

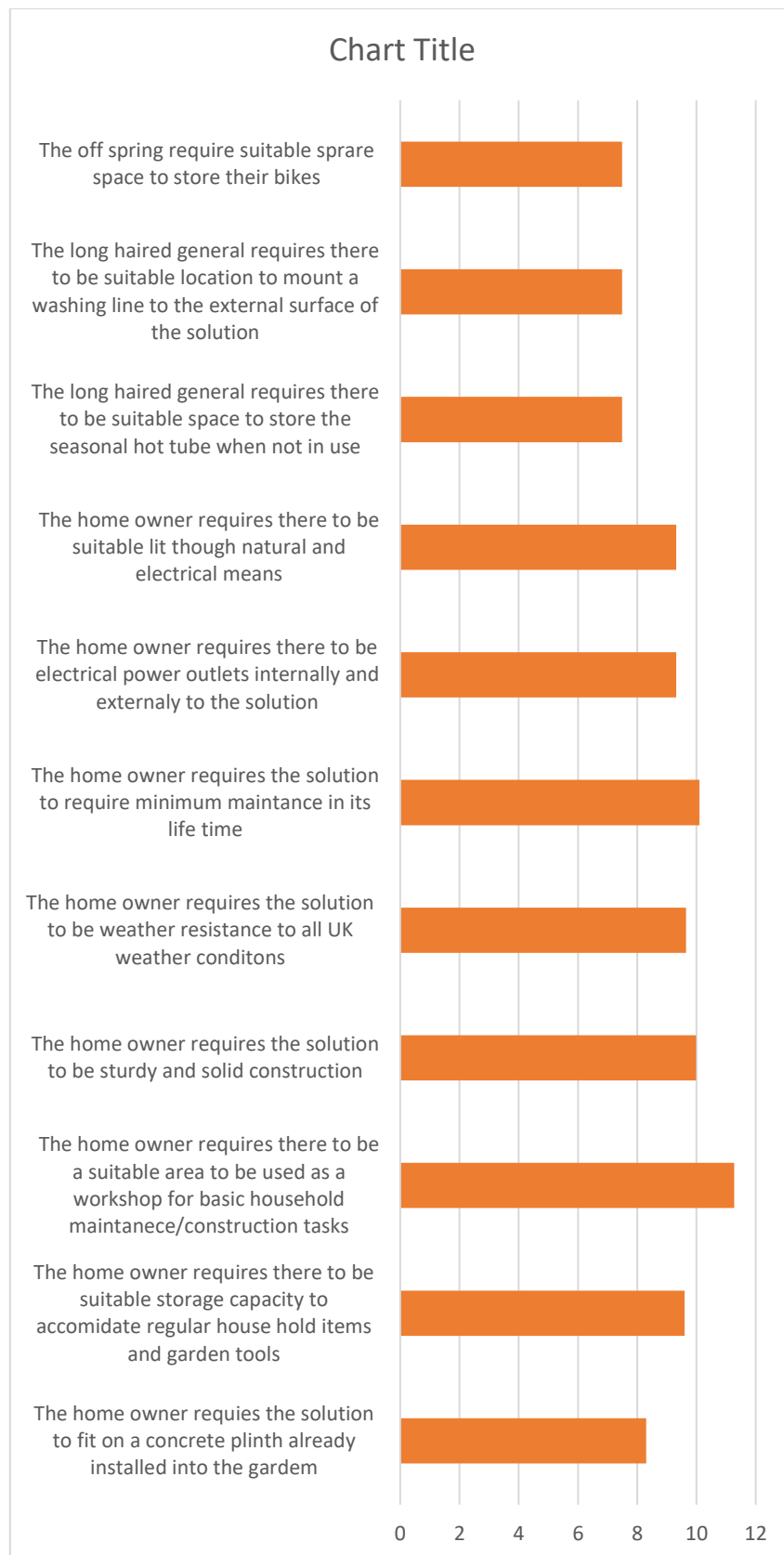


Figure 1: Results of the pairwise comparison.

Critical System Functionality

Critical system functionality is an approach used to ensure the systems core functions meet the needs stated in the requirements [6]. To undertake this approach, you need to undertake a 2 steps process, Analysis of system functions and Mapping customer requirements to system functions.

Once the requirements have been established to an initial level, functional analysis needs to be undertaken. Analysis from an engineering approach is generally the breaking down of an item, system, issue, or solution into its simplest form to understand its features and the relationship between the components. A Functional analysis is the breakdown of what a system does, in relation to the functions it performs, typically excluding the how its performed due to the How being part of the design solution [7]. This is typically done by identifying and documenting all the functions the system needs to perform, evaluating them against the requirements by understanding what each of the functions are and how they contribute to achieving the requirements. This is done by mapping the customer requirements to the system functions. This ensures the customers' needs have been met by a function within the system [7].

For the case study the system functions were extracted from the requirements, were as follows:

- Store Items.
- Space to work.
- Provide power.
- Weather resistance.
- External mounting options.

In this stage the mapping of customer requirements to system functions can be completed along with analysing the relationship between them using the design QFD1. The output from this analysis can be seen below in table 4.

In the table it can be seen an importance level has been applied to each of the requirements on a scale of 1 to 5, with 5 being the most important and 1 being least. Once this scale was applied an analysis of the relationship between each requirement and system functions was undertaken where a value of either strong (9), medium (3) or Weak (1) was applied. Any box with a zero demonstrates no relationship between that requirements and system function.

How	Importance	Store items	Work space	provide power	weather resistance	external mounting option
Requirements						
The home owner requires the solution to fit on a concrete plinth already installed into the garden	3	3	3	1	1	1
The home owner requires there to be suitable storage capacity to accomidate regular house hold items and garden tools	5	9	3	1	3	1
The home owner requires there to be a suitable area to be used as a workshop for basic household maintanece/construction tasks	5	9	9	3	3	1
The home owner requires the solution to be sturdy and solid construction	3	1	3	1	9	3
The home owner requires the solution to be weather resistance to all UK weather conditons	3	1	1	1	9	3
The home owner requires the solution to require minimum maintance in its life time	4	0	1	1	9	1
The home owner requires there to be electrical power outlets internally and externaly to the solution	2	0	3	9	1	1
The home owner requires there to be suitable lit though natural and electrical means	2	0	3	3	3	1
The long haired general requires there to be suitable space to store the seasonal hot tube when not in use	2	3	1	1	1	1
The long haired general requires there to be suitable location to mount a washing line to the external surface of the solution	1	0	1	1	1	9
The off spring require suitable sprare space to store their bikes	1	3	1	1	1	1
		114	101	61	135	51

Table 3: QFD 1

From this QFD 1 analysis a functional importance graph can be produced showing which of the functions is the most important in meeting the requirements set by the customer. This graph is shown below in figure 2. The results from the graph show that the key functional requirement is for the structure to be weather resistance, followed by being able to store items (suitable internal space) and closely followed by Workspace (meaning suitable working space after storage requirement has been met). It also shows that functional requirements of being able to externally mount things and provide power within the

structure although important should not be the driving factor when considering design concepts.

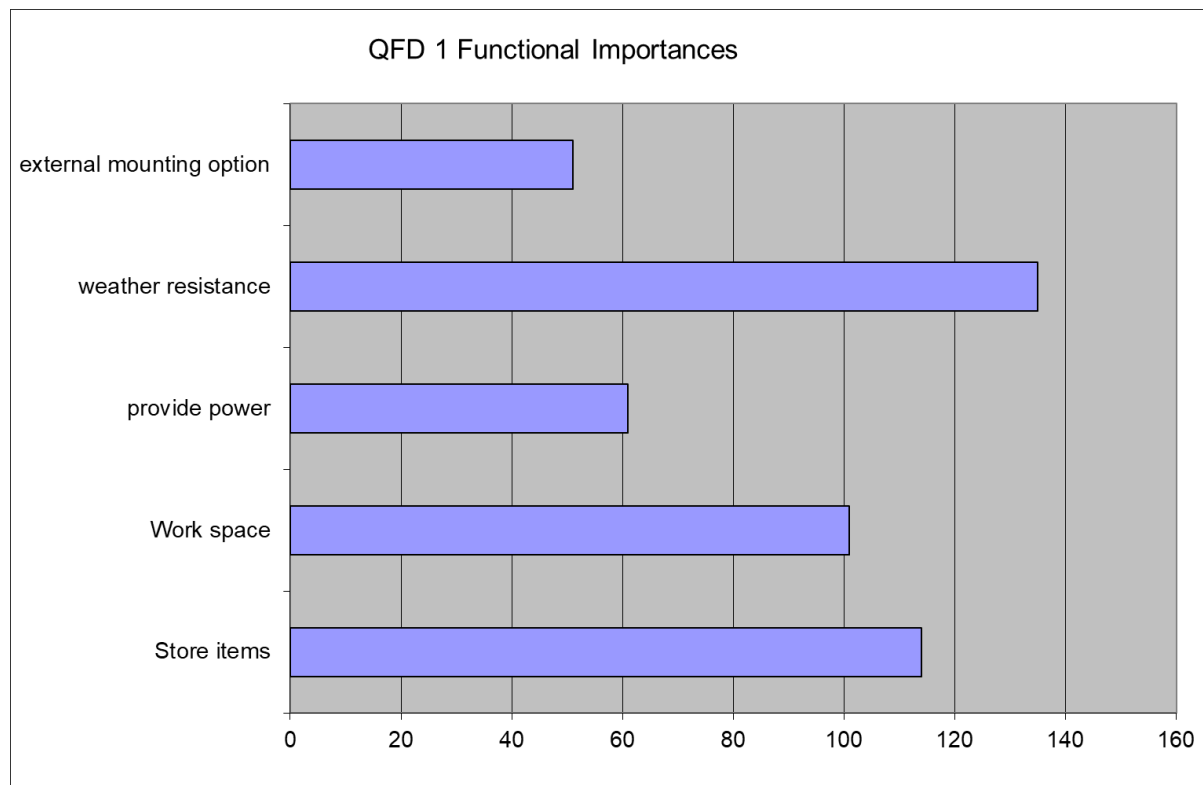


Figure 2: Functional importance.

Following completion of the QFD 1 analysis an attempt at concept derivation and design choices can be undertaken and will be discussed in the next section.

Concept Derivation, Design Choices & Critical design features

Concept derivation is the process of breaking down the requirements to identify key needs to help find a solution to the problem that is being solved. This approach uses the key requirements to help formulate a suitable approach to address the needs of the customer [8]. In the regards to the case study of replacing a shed, the key requirements identified at the end of the previous section where the needs for it to be weather resistance and have suitable internal space not only for storage but also to allow enough room for it to be used as a small workshop.

From these requirements a brainstorming exercise can be undertaken exploring all possible design solutions to meet the requirements. This exercise was conducted against all the functional requirements (some requirements were grouped together due to the cross over between the two (storage and workspace requirements) and the following solutions were identified for each of the sections:

Store items/Workspace:

- Off the shelf purchase wooden shed (premade).
- Custom built shed.
- Brick built building.
- Shipping container.

Provide power:

- Solar panels.
- Mains power supply.
- Wind turbine.

Weather resistance:

- Plastic coated.
- Insulated.
- Metal roof.
- Tile roof.

External mounting options:

- Wooden exterior.
- Brick exterior.

These solutions were then put through functional means analysis where the most appropriate solutions were highlighted. This process also identifies critical design features, these are essential areas that ensure the solution is effective at meeting the requirements. These features are used to guide the design process and makes sure the final design meets the requirements and expectations of the customer. Some key areas to consider as part of this process are:

1. **User-centricity:** Ensuring the design solution meets the customers' requirements/expectations.
2. **Feasibility:** Ensuring the solutions is technically possible and is within the customer's budget.
3. **Scalability:** Making sure the design solution can meet the future needs of the customer as the requirements grow/change.
4. **Sustainability:** Does the solution provide a long-term solution to the requirements.

By using this approach, it helps create a robust and appropriate solution to the requirements but also ensures long term effectiveness at meeting their requirements [9].

The results from the functional means analysis have highlighted the critical design features that are to be taken forward to meet the requirements of replacing the garden shed. A Shipping container, Custom built shed or a brick building have been considered for the next stage of the analysis. An off the shelf shed has been discounted from the possible solutions

due to the costs and the inability to adjust the design to meet the requirements. In regard to providing power to the solution, solar power and wind power solutions were discontinued due to do the additional costs and technical difficulty of incorporating them into the final solution. Specifically, when taken into consideration the fact there is already an mains supply cable in place at the location the solution will be situated. For weather resistance the most cost-effective way after researching the possible solutions was to use a metal galvanised roof to add additional weather resistance. The use of insulation was also selected to help reduce the large temperature variations experienced by an outdoor and unheated structure. The use of insulation will help maintain a constant temperature within the solution helping to prolong the life of volatile items stored within (paints, oils etc). The final consideration going forward that met the functional requirements the most was the use of wood on the external surfaces of the solution, due to the easy of mounting items to the exterior.

Function	Means			
Store items	Shipping container	off the shelf shed	custom built shed	brick building
Work space	Shipping container	off the shelf shed	custom built shed	brick building
provide power	Solar pannels	Mains supply cable	wind turbine	
weather resistance	plastic coated	insulation	metal roof	tile roof
external mounting option	Wooden outside	Brick outside		

Figure 3: Functional means analysis and critical design features.

The next stage was to proceed with the highlighted solutions into a QFD 2 against the requirements, here as with the QFD 1 discussed above a weight of low, medium, and high was used to measure the relationship between the requirements and the possible solution. Table 3 below shows the completed QFD 2 table. It is worth noting there are significantly more blank spaces compared to the QFD 1 table above, this is due to the fact certain solutions do not have a relationship with certain requirements, for example the solution of using insulation has no bearing on the requirements to fit on an existing concrete plinth.

Design feature	Importance	Shipping container	custom built shed	brick building	Mains supply cable	insulation	metal roof	Wooden outside
Functionality								
The home owner requires the solution to fit on a concrete plinth already installed into the garden	3	3	9	9				
The home owner requires there to be suitable storage capacity to accomodate regular house hold items and garden tools	5	3	9	9				
The home owner requires there to be a suitable area to be used as a workshop for basic household maintanece/construction tasks	5	3	9	9				
The home owner requires the solution to be sturdy and solid construction	3	3	9	9		3	3	3
The home owner requires the solution to be weather resistance to all UK weather conditons	3	3	9	9		9	9	3
The home owner requires the solution to require minimum maintance in its life time	4	3	3	3		3	3	3
The home owner requires there to be electrical power outlets internally and externaly to the solution	2				9			
The home owner requires there to be suitable lit though natural and electrical means	2	1	3	3	1			
The long haired general requires there to be suitable space to store the seasonal hot tube when not in use	2	3	3	3				
The long haired general requires there to be suitable location to mount a washing line to the external surface of the solution	1	1	9	3				9
The off spring require suitable sprare space to store their bikes	1	1	1	1				
		79	205	199	20	48	48	39

Table 3: QFD 2

As with the QFD 1 exercise there is a features important graph produced from the results of the QFD 2 table, which can be seen below in figure 4. It is worth pointing out that although the graph is shown as one picture it should be noted that some of the features are not grouped together. For example, the type of solution (shipping container, custom shed, brick building) should be compared together as they are competing solutions. But the remaining four features within the graph can be considered as the final solution to these requirements

as there is no competing elements between them, they are either entirely separate from each other (Mains power supply) or the complement each other (metal roof & Insulation).

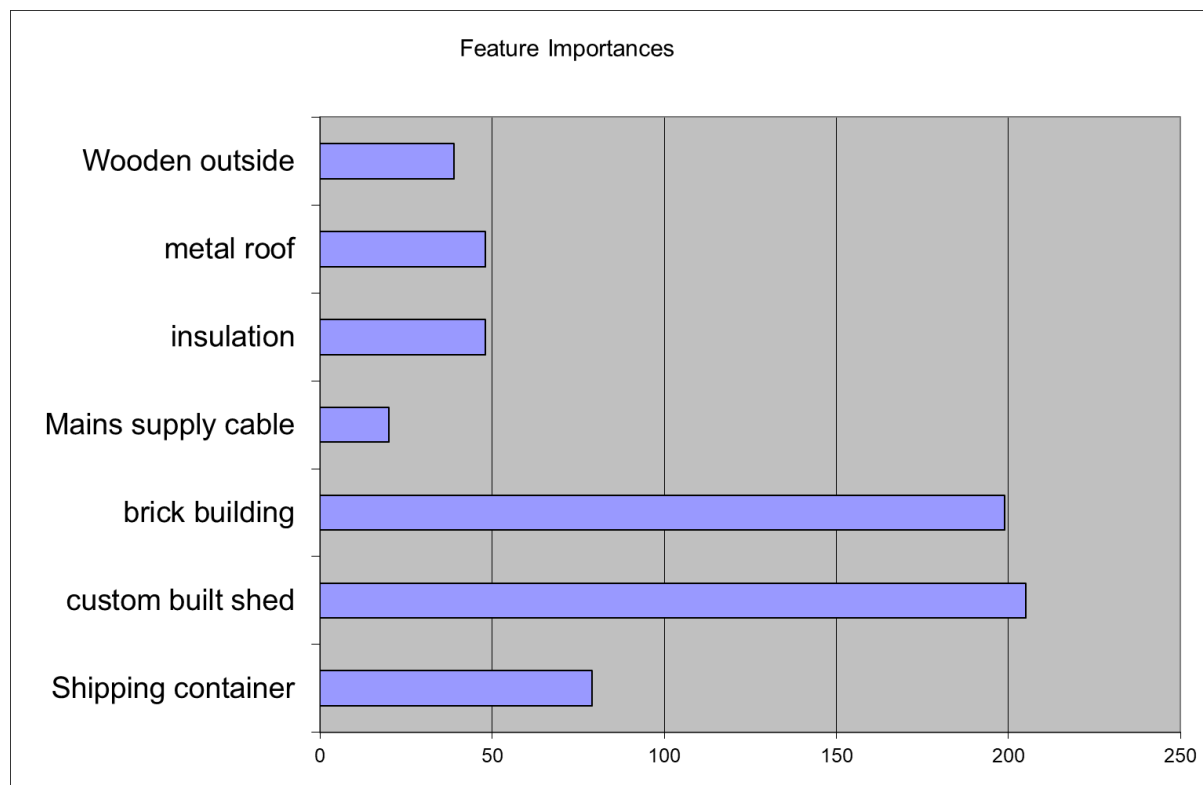


Figure 4: QFD2 Features importance.

With the above statement in mind the three possible solutions were put through a system Pugh. A system Pugh better known as a Pugh Matrix or criteria rating form is a tool used to evaluate the best solution to a problem after identifying the relevant user requirements. This is achieved by comparing each possibly solution against the identified user requirements [10]. The simplest way to describe this process is very similar to that of the game top trumps, each solution is given a score on how well it meets that requirement, and the solution with the best overall score is deemed to be the most suitable. By using this approach, the Pugh tool can easily and simply breakdown a complex requirement sets into chunks that can be easier compared help to show how a final solution was chosen [10].

The first step taken in the Pugh matrix was to assign a weighting to all of the user requirements, this was done with a rating of 1 to 9 with 9 being the highest (most crucial) and 1 being the lowest (least crucial). This rating range was then applied to the three possible solutions with 9 showing the solution fully met that requirement and 1 showing the solution did not meet this requirement at all. This assessment can be seen below in table.

Garden shed replacment

		Relative Importance Equal	Relative importance Weighted	Shipping container	Custom shed	Brick building	
WHATs - Customer Requirements	How much:- From QFD 1						
The home owner requires the solution to fit on a concrete plinth already installed into the garden		3	9	0	9	9	
The home owner requires there to be suitable storage capacity to accomidate regular house hold items and garden tools		5	9	5	5	5	
The home owner requires there to be a suitable area to be used as a workshop for basic household maintanece/construction tasks		5	9	4	5	5	
The home owner requires the solution to be sturdy and solid construction		3	5	4	6	6	
The home owner requires the solution to be weather resistance to all UK weather conditons		3	5	4	5	5	
The home owner requires the solution to require minimum maintance in its life time		4	5	4	5	4	
The home owner requires there to be electrical power outlets internally and externaly to the solution		2	3	3	3	3	
The home owner requires there to be suitable lit though natural and electrical means		2	3	3	5	5	
The long haired general requires there to be suitable space to store the seasonal hot tube when not in use		2	3	4	4	4	
The long haired general requires there to be suitable location to mount a washing line to the external surface of the solution		1	1	2	6	2	
The off spring require suitable sprare space to store their bikes		1	1	4	4	4	
Ranking				111	164	156	0
				177	297	288	0
		100		-66	-133	-132	0

Table 4: System Pugh

The results of this system Pugh shows that the shipping container solution was the worst performing of the solutions. The custom shed and brick building had very similar results from this assessment with the Custom shed having a single digit better score over its counterpart.

Potential Failure Modes

As this case study was conducted against a problem faced by the author of this assignment in a personal matter and after its conclusion. Not every step of this case study was undertaken in a manner that would be typically undertaken by a large organisation facing a similar problem and one of these steps was to cover potential failure modes by conducting a Failure modes and Effects Analysis (FMEA).

By conducting a FMEA potential disasters or issues could have been identified before they happened. By conducting an in-depth review before commencing the construction phase design mistakes, construction issue and difficult areas could have been identified and have mitigations put in place before they were encountered; by doing this it ensures a quality product can be delivered [11].

There are numerous steps that must be undertaken for a successful FMEA, by following the steps laid out below a project can easily identify and resolve issues ahead of time [11].

1. **Define the scope:** This step needs to clearly outline the construction process and should include all steps from groundwork to finishing touches.
2. **Gather all construction stakeholders:** It is important to include all key persons used in the construction of the solution such as design, carpentry, electricians, and foundation setters, to name a few. This ensures all areas are covered.
3. **Identify potential failures:** Brainstorming of all potential failure modes for each and every step of the construction process. Issues such as foundation setting, incorrect measurements or materials quality are to be considered.
4. **Assess severity (S), Occurrence (O) and Detection (D):** This step involves assessing the severity of the failure if it was to happen, the likelihood of this failure happening and also how this issue can be detected before it happens. These three aspects are assigned a number, for simplicity in this case 1 to 5 (1 least concerning and 5 most concerning). These numbers are then used in the next stage.
5. **Calculate Risk priority number (RPN):** In this stage each of the three number assigned to a potential failure mode in the previous step are then multiplied to give a risk priority number. For example, $RPN = S \times O \times D$. By doing this the most severe or likely failure to happen can be identified and highlighted as the most concerning.
6. **Develop action plans:** This step is where mitigations can be identified and produced, then put in place to reduce or eliminate the failure modes. These could be quality control checks or use alternative materials.
7. **Implement changes:** This stage is where the mitigations are used during the construction stage.
8. **Monitor and review:** As with all failure mitigations continuous monitoring and reviewing should be undertaken throughout the duration of the project to ensure all mitigations are still suitable and appropriate for the project.

If this step was undertaken before the project commenced, it could have identified an issue faced during the construction process. The issue faced during the construction of the base of the shed, was it was assumed the already existing concrete plinth was square and as such the base was constructed to ensure it was as square as possible. When the base was moved into place it was seen that the plinth was not square and as a result one corner of the base stuck out and floated in the air instead of providing a solid point to spread the weight. This solution was overcome in the end but provided a prime example of how a FMEA could have prevented such issues.

Manufacturing Processes

Essentially QFD 1 & 2 but from a manufacturing point of view

During any large-scale project there is a constant flow of steps and processes needed to progress the project to conclusion. As the case study in this assignment was based around a bespoke single item it's not possible to fully cover all the steps and demonstrate an appropriate process flow for describing the perfect system engineering approach to a problem. Therefore discussion around manufacturing in this section and process control measures will only loosely follow the case study (where appropriate examples exist from this project) and the bulk of the processes covered to describe manufacturing process will mainly focus on a hypothetical approach on the best practices, like the previous section covering potential failure modes.

The next stage in a system engineering approach is to conduct phase 3 of the project also known as QFD3. In this stage of the project the focus moves on from design/concept derivation and into the manufacturing processes required to produce the solution to the requirements. This is done through QFD 3 also known as the process planning matrix. This step translates product requirements highlighted in QFD 2 into a series of requirements needed to meet the solution [12]. For example, in the case study this would be identifying the process steps of constructing the shed. From constructing the frame, to covering the frame, waterproofing the construction and so on until the item is constructed. To complete this there are three steps that must be undertaken:

1. **Identifying critical manufacturing processes:** Identifying essential processes required to meet the product specification.
2. **Defining process parameters:** This stage is about controlling the parameters (such as dimensions or materials) to ensure the solution meets the requirement.
3. **Mapping process steps:** This stage sets out the step-by-step approach to completing the project.

After the completion of this stage the next step is to phase 4 or QFD 4. This stage in a traditional approach would be used to take an item and look at how to implement the processes identified in the previous stage and typically at a larger scale than one off or prototyping. This stage ensures the processes identified in QFD 3 are developed enough and capable of producing the required solution, the three-stage approach to doing this is [12]:

1. **Developing production schedules:** This stage plans the timings and sequences around the production processes. Ensuring the right items are delivered at the right time, similar to those employed by the car manufacturing sector called Just in Time.
2. **Implementing quality control measures:** This stage implements quality control measures used to ensure the product continues to be manufactured to specifications.
3. **Conduct pilot runs:** As with any large-scale production runs there needs to be a test run to ensure the processes put in place produce a product that meets the requirements. This can also identify and address any issues before large scale production commences.

By undertaking this systematic approach, the QFD stages ensure the needs of the customer have been met in every stage of the project and helps ensure all parties involved are working in synergy.

As mentioned above this case study focused on a single bespoke item so unfortunately did not go through a full QFD 3 & 4 process. A very loose approach was taken to ensure all stages of construction were completed. A Gantt chart in appendix B shows the stages the project went through from design to completion showing a production schedule and sequencing that was followed.

Process Control Measures

Process control measures is the next stage that falls out of manufacturing processes, very similar to QFD 4 but with a focus on full scale production, ensuring the product constantly produces a high-quality product [13]. As with the previous stage there was no large-scale production for the case study so it is not possible to talk about this stage using the case study, but the following section will describe how this process should be undertaken.

To conduct and implement process control measures the following steps must be undertaken [13] [14]:

- **Identify key process variables:** This step identifies anything that can vary during the all the stages of manufacturing from material quality, to supply chain issues, weather or anything that can affect the outcome of the item.
- **Monitoring systems:** Once the variables have been identified there needs to be a way of monitoring these variables as without this step there is no way of identifying when a variable is starting to have an impact on the project.
- **Establish control limits:** This stage defines acceptable limits these variables can have (a tolerance), this needs to ensure the limits are based on a specification to ensure a quality product is continued to be delivered.
- **Statistical process control:** This step ensures the data collected during the monitoring step is analysed with the help of charts and visualisation aids to show how the production process is meeting the limits and helps to detect variations which might indicate a problem.
- **Conduct regular inspections and audits:** Regular inspections and audits of the process ensures the manufacturing process continues to meet the limits and that the limits set are still appropriate. This stage could involve batch testing or sampling.
- **Continuous improvement:** This stage uses all the previous stages data and insight to optimise the production processes. This could be achieved by adjusting the production sequence, upgrading equipment, or refining operation processes.
- **Documentation:** With any manufacturing process it is important to document every step and stage of a project. This should include any deviations and steps taken to resolve them. This stage is important to maintaining a quality standard and helps with troubleshooting any issues.

This stage could be considered as a safety tether for the production stage, it ensures the product continues to meet the desired standard.

Conclusion

This assignment has covered systematic approach that should be taken for any complex project, covering the essential steps needed for there to be a successful outcome. These were covered by explaining QFD 1 to 4 and used a case study as an example of where these steps should be used.

In QFD 1 the customer needs were identify and prioritised, to lay the framework for a suitable solution. QFD 2 used these requirements to find the technical specifications ensuring the design incorporates critical features and functions. QFD 3 moves on from design and into manufacturing where the process needed to complete successful manufacturing of the solution are fleshed out. In the final step QFD 4 the manufacturing steps moves into a production planning stage which sets out the steps needed for continuous manufacturing process that continues to meet the customers' requirements.

Although the case study used as an example did not fully follow all the steps described, it was still useful as a demonstration piece showing how the key steps can be used to progress a project. Even though not every step was followed in the case study, the stages where these steps were missed were used to show how these steps could have improved the project in the case study. They also showed how these steps could have prevented a couple of the issues experienced by the project. The final product used in the case study can be seen below in Appendix C.

By following this systematic approach it enhances the final products quality, it also helps facilitates cross functional collaboration that is essential for a successful system engineering approach. By following this approach customer needs and requirements are translated into actionable plans, better meeting these requirements and producing at a lower cost. The QFD approach is a great tool used to deliver a suitable solution to a set of customer requirements, it ensures every step, from initial concept to final productions meets the overarching goal of delivering a solution to the customer.

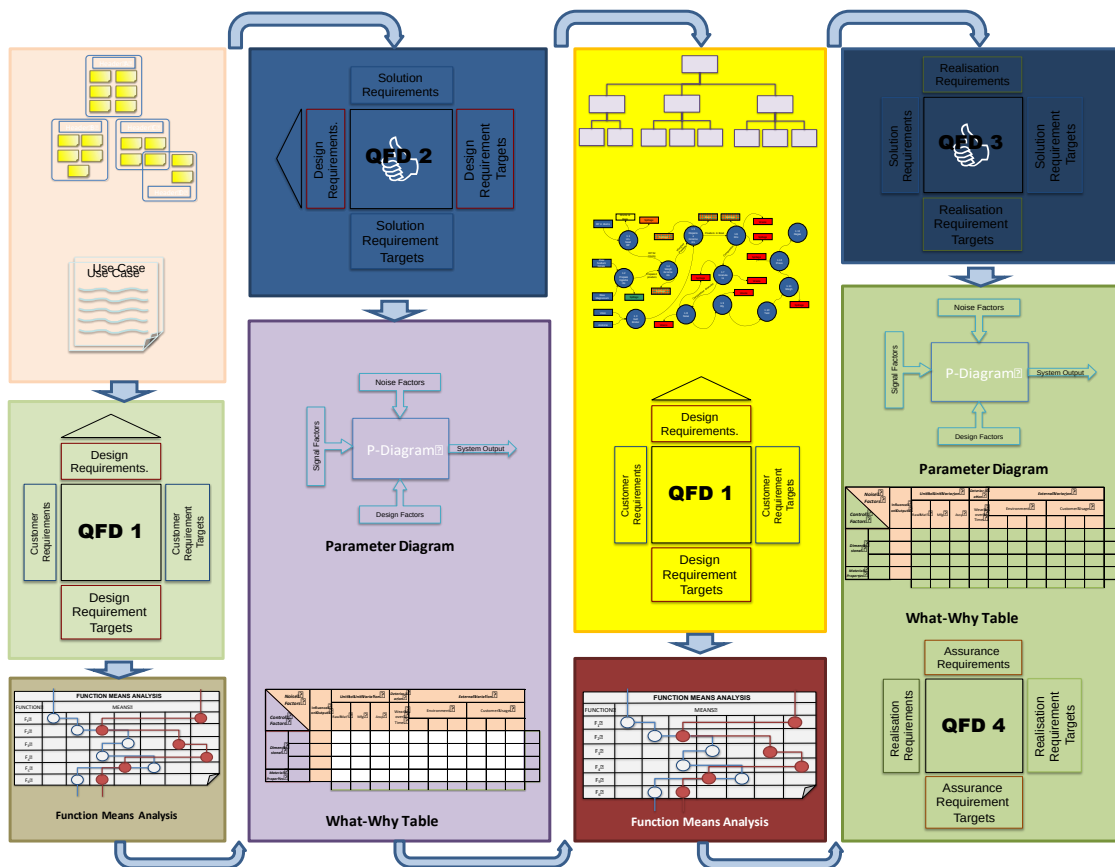
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Appendices

Appendix - A: Design workbook

Design Book		
Garden storage and workshop solution		
Teamcentre Document Number	Issue	Date
Garden storage solution 1		date issued



Appendix – B: Project Gantt chart

Project Planner

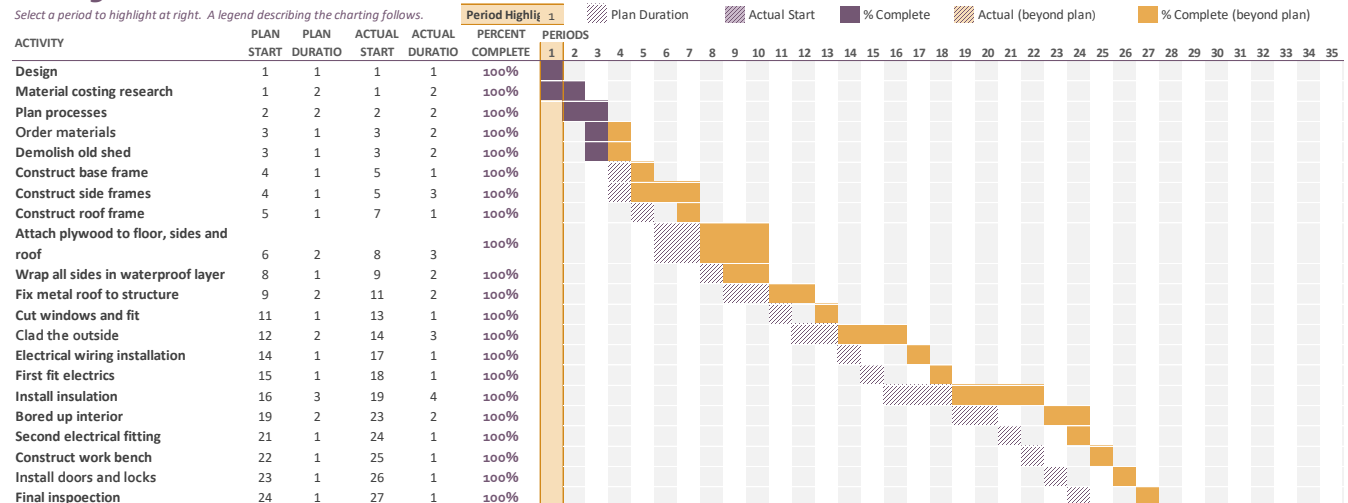


Table 5: Project Gantt chart

Appendix – C: Case study product

The final solution met all the required identified in QFD 1, table 6 below shows how these requirements were met, and photographs of the final solution can also be seen below.

Originator	Requirements	Final solution
Homeowner	The homeowner requires the solution to fit on a concrete plinth already installed into the garden	The wooden shed fit on the concrete plinth despite the plinth not being square. The design was adjusted to meet this requirement
Homeowner	The homeowner requires there to be suitable storage capacity to accommodate regular household items and garden tools	Shelving was added around the inside of the shed. Due to the shelves all items needed to be stored within the shed had plenty of room to meet this requirement. Seen below in figure 5
Homeowner	The homeowner requires there to be a suitable area to be used as a workshop for basic household maintenance/construction tasks	Due to the shelves above freeing up floor space a work bench could be made to fit within the shed. This provided adequate space for the requirements. Seen below in figure 5
Homeowner	The homeowner requires the solution to be sturdy and solid construction	The solution was constructed out of 4x6 wooden beams providing a solid and sturdy construction.
Homeowner	The homeowner requires the solution to be weather resistance to all UK weather conditions	The solution used a varied of methods to meet this requirement. In between the structural frames was filled with 100mm thick insulation on

		all sides. The frame was then covered inside and out with 9mm thick plywood sheets. The outer plywood was then covered in a waterproof but breathable membrane. The roof used galvanised metal sheets to provide a low-cost maintenance free roof. Finally the outside of the shed was clad in thick wooden board providing extra protection to the inside.
Homeowner	The homeowner requires the solution to require minimum maintenance in its lifetime	The final solution incorporated 2 key components to achieve this requirement. The first was metal galvanised roof sheets the second was in the choice of wood type used for the external cladding. The external wooden cladding seen below in figure 4 is made of cedar which is naturally rot resistance and requires no maintenance due to the natural oils contained within the wood.
Homeowner	The homeowner requires there to be electrical power outlets internally and externally to the solution	Electrical power was supplied by an already existing mains supply cable from the main house. There were 6 internal and 2 external electrical outlets installed on the shed.
Homeowner	The homeowner requires there to be suitable lit though natural and electrical means	Two high power lights were installed within the shed provided ample lighting for using the shed as a workshop.
Long-haired general	The long-haired general requires there to be suitable space to store the seasonal hot tube when not in use	All though not shown in figure 4 below the external washing line was installed onto the outside of the shed.
Long-haired general	The long-haired general requires there to be suitable location to mount a washing line to the external surface of the solution	There was an appropriate location to store the hot tub within the shed without impacting any other requirements for storage or workspace.
Offspring	The offspring require suitable spare space to store their bikes	There was suitable space to store bicycle within the shed

Table 6: How each requirement was met



Figure 4: Outside of the Shed



Figure 5: Inside of the shed.