

University of Wales Trinity Saint David

Design and Manufacture Case Study

Systems Engineering Assignment

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Abstract

This assignment explores the use of systems engineering tools in the design of new products. By applying systems engineering tools such as Quality Function Deployment 1-4, functional analysis, Failure Modes and Effects Analysis, and process control measures, the design process can satisfy customer needs while ensuring manufacturability and quality control. As a demonstration of how these tools can be helpful, this assignment primarily consists of the use of these tools in designing a rocket motor igniter.

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Definitions and Acronyms

QFD	Quality Function Deployment
EDB	Extruded Double Base
SAD	Safety Arming Device
FFBD	Functional Flow Block Diagram
EBW	Exploding Bridge-Wire
FMEA	Failure Modes and Effects Analysis
RPN	Risk Priority Number
RLC	Resistance, impedance, capacitance
PCR	Production Control Round
PFMEA	Process Failure Modes and Effects Analysis

Introduction

Systems engineering is an interdisciplinary field that focuses on designing and maintaining complex systems across their lifecycles. A systems engineering approach to design involves the use of systems engineering tools, such as Quality Function Deployment (QFD) which helps align the final product with customer expectations. The use of systems engineering tools reduces development times and costs by 'left shifting' design decisions which allows any errors to be found earlier in the process. This document aims to demonstrate the utility of systems engineering tools in the development and design of new products.

This document will discuss the design of a rocket motor igniter. As the name would suggest, the igniter is responsible for igniting the main propellant charge within the rocket motor. Thus, it's design and performance are critical to the functionality of the overall system. The general construction of an igniter consists of an ignition source (often electric), sensitive pyrotechnic powders, pyrotechnic pellets, a propellant charge (typically Extruded Double Base (EDB) propellant, referred to as a pyrogen), all of which are contained within a metal case. The igniter ignites the main propellant of the rocket motor by ejecting hot gases and combustion products onto the surface of the main charge.

This document does not contain commercial or security sensitive information. All discussion of igniter design assumes a theoretical igniter and does not imitate an existing design except if open-source information is referenced.

The Design Process

This section aims to demonstrate how systems engineering tools assist the design process via the identification of each of the respective sub-headings. The design process for a rocket motor igniter will be used throughout.

Key Customer Requirements

When designing a product, it is vital to understand customer requirements for the product to satisfy them. Customer requirements can be misunderstood for a variety of reasons, such as poor communication, miscommunication, the customer not being certain about what they want, etc. The result of not getting customer requirements right is designing a product that does not fulfil the

desired function. Thus, the first step when designing a product is always to produce a list of a customer requirements that the customer can confirm.

QFD 1 is a systems engineering tool that can be used to translate customer requirements into technical requirements for product development [1]. The first step of QFD 1 is to identify the customer requirements. In our example of an igniter, this might include:

Low mass	Resistance to radio frequencies
Short ignition delay	An arming system
Reliable operation of the explosives train	Long lifecycle duration
Reliable ignition of main charge	Good insensitive munitions properties
Redundancy in the ignition circuit	Capability at both temperature extremes

Once the customer requirements are established, they must be given a weighting based on the importance of the customer requirement. Below, this will be done by rating each requirement on a scale of 1-10 where one is least important and ten is most important.

Low mass	3	Resistance to radio frequencies	6
Short ignition delay	5	An arming system	6
Reliable operation of the explosives train	10	Long lifecycle duration	9
Reliable ignition of main charge	10	Good insensitive munitions properties	6
Redundancy in the ignition circuit	4	Capability at both temperature extremes	8

The next step is to determine the design requirements by listing engineering or product characteristics that would satisfy the customer requirements.

Low mass	Minimal energetic material to achieve function
Short ignition delay	Use an exploding bridge-wire (EBW) design
Reliable operation of the explosives train	Excess energy between explosive train stages
Reliable ignition of main charge	Excess energy from final booster
Redundancy in the ignition circuit	Safety arming device (SAD) with two lines
Resistance to radio frequencies	Use a SAD
An arming system	Use a SAD
Long lifecycle duration	Use energetics that degrade slowly
Good insensitive munitions properties	Use energetics that are resistant to friction and shock
Capability at temperature extremes	Good energetic performance at all temperatures

The next step is to create a House of Quality matrix which relates the customer requirements to the design requirements. Within the House of Quality matrix, relationships are rated as either strong (9), medium (3), or weak (1). This can be seen in Table 1.

		Customer Requirement Weighing	Design Requirements								
			Minimal energetic material to achieve function	Use an EBW design	Excess energy between explosive train stages	Excess energy from final booster	SAD with two lines	Use a SAD	Use energetics that degrade slowly	Use energetics that are resistant to friction and shock	Good energetic performance at all temperatures
Customer Requirements	Low mass	3	9	3	1	1	1	1	1	1	1
	Short ignition delay	5	3	9	3	3	3	1	1	1	3
	Reliable operation of the explosives train	10	1	9	9	9	9	1	3	1	9
	Reliable ignition of main charge	10	1	3	3	9	3	1	3	1	9
	Redundancy in the ignition circuit	4	1	1	3	1	9	1	1	1	1
	Resistance to radio frequencies	6	9	9	1	1	9	9	9	1	1
	An arming system	6	3	1	1	1	9	9	1	1	1
	Long lifecycle duration	9	1	1	1	1	1	1	9	1	1
	Good insensitive munitions properties	6	9	3	1	1	3	3	3	9	1
	Capability at temperature extremes	8	1	1	3	3	1	1	3	1	9
Design Requirement Priority			209	273	201	253	317	175	255	115	301

Table 1 – QFD 1 to determine design requirement priority.

The output of the QFD 1 table is the design requirement priority. This tells the author which design requirements must be prioritised to satisfy customer requirements. For the igniter design, the design requirement priority order is:

1.	SAD with two lines	317
2.	Good energetic performance at all temperatures	301
3.	Use an EBW design	273
4.	Use energetics that degrade slowly	255
5.	Excess energy from final booster	253
6.	Minimal energetic material to achieve function	209
7.	Excess energy between explosive train stages	201
8.	Use a SAD	175
9.	Use energetics that are resistant to friction and shock	115

Based on this QFD 1, the priority feature of a new igniter to meet customer requirements is a SAD with two ignition lines for redundancy. By contrast, using energetics that are resistant to friction and shock is not as important to meet this set of customer requirements.

Critical System Functionality

When designing a system or product it is important to clarify how it will achieve its goals. This is done by breaking it down into functional components to identify critical system functionality.

Functional analysis is a systems engineering tool that can be used to break down systems into functional components. The first step of functional analysis is to define the system's purpose. The main purpose of the rocket motor igniter is to use an electrical current to safely and reliably ignite the main charge of the rocket motor.

This top-level function is then broken down into sub-functions that describe how the system will achieve its purpose. The sub-functions of an igniter that employs a SAD might be:

Receive arming signal
 Display armed status on visual indicator
 Move ignition train into line
 Receive firing signal
 Use firing signal to initiate ignition train
 First energetic initiate second energetic
 Second energetic initiate third energetic
 Third energetic initiate main charge

The next stage is to create a Function Flow Block Diagram (FFBD) that visually represents the sub-functions and lays out their logical flow. Figure 1 shows the FFBD for the igniter.

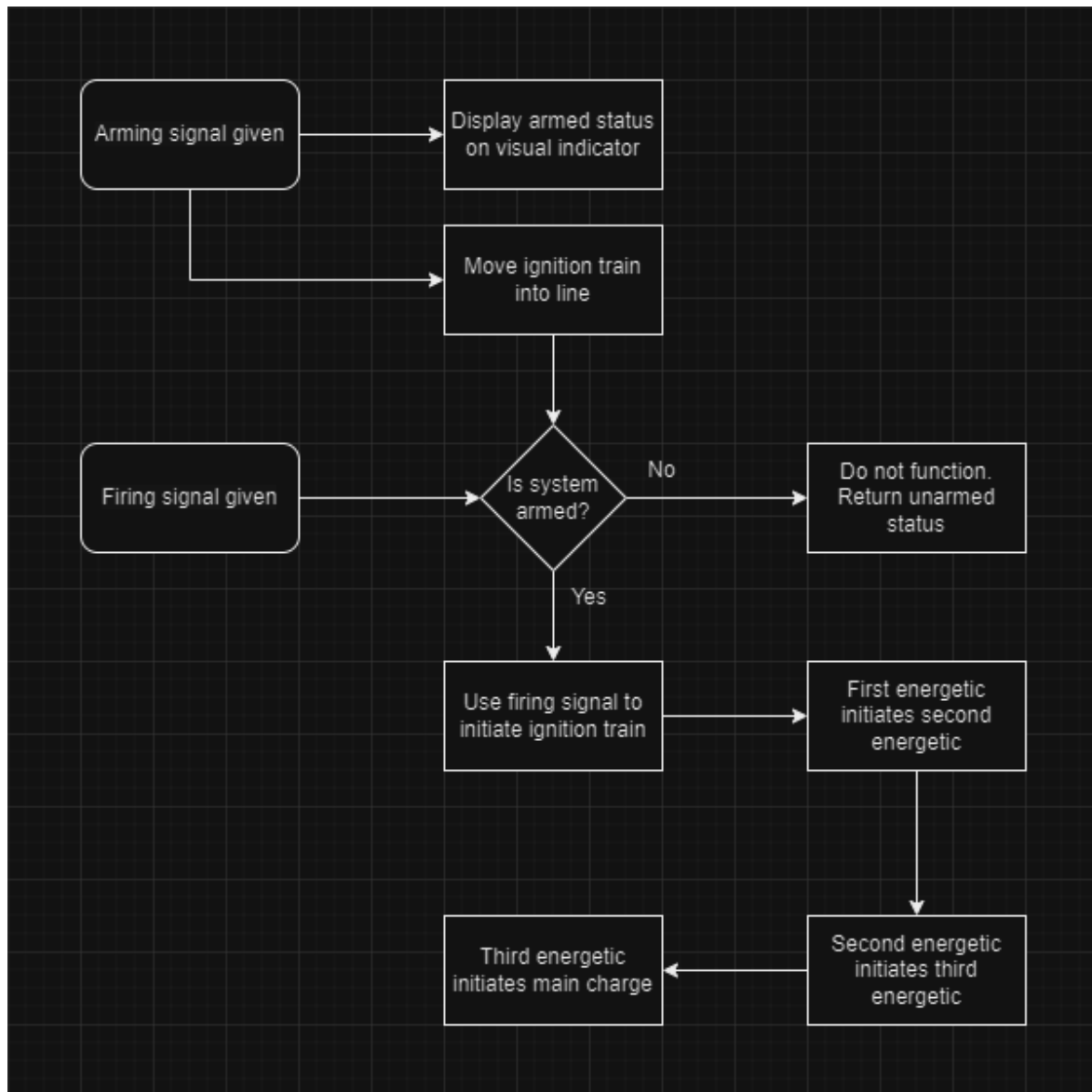


Figure 1 – FFBD demonstrating how igniter sub-functions work together to achieve the system purpose.

Once the sub-functions of the igniter are understood, the critical functions can be determined. Critical functions are ones that significantly undermine the ability of the system to achieve its function when they fail. The critical functions of this system are:

Moving the ignition train into line
Electrically initiating the ignition train
Propagation of initiation through ignition train
Initiation of the main charge

If this fails, the ignition train cannot function
If this fails, the ignition train won't function
If this fails, the ignition train will partially function
If this fails, the purpose of the igniter isn't fulfilled

Sub-functions must then be analysed to see if there are any functional interactions to identify potential dependencies or risks.

Display armed status on visual indicator
Move ignition train into line
Use firing signal to initiate ignition train
First energetic initiate second energetic
Second energetic initiate third energetic
Third energetic initiate main charge

Dependent on receiving arming signal
Dependent on receiving arming signal
Dependent on system being armed
Dependent on function of preceding energetic
Dependent on function of preceding energetic
Dependent on function of preceding energetic

As demonstrated, failure in some sub-functions can cause others to fail.

Next the inputs and outputs of each sub-function must be identified. This clarifies how the system works and the relationships between sub-functions.

Sub-Function	Input	Output
Receive arming signal	Operator input	Arming signal
Display armed status on visual indicator	Arming signal	Visual indicator displayed
Move ignition train into line	Arming signal	In-line ignition train
Receive firing signal	Operator input	Firing signal
Use firing signal to initiate ignition train	Firing signal	Heat
First energetic initiate second energetic	Heat	Heat
Second energetic initiate third energetic	Heat	Heat
Third energetic initiate main charge	Heat	Heat

As a result of this functional analysis, the critical functions and dependencies within the system are understood. This influences the design by prioritising the design of certain components.

Concept Derivation and Design Choices

Once the design requirements and the critical system functionality are understood, a concept can be derived, and design choices made. The systems engineering tool to achieve this is QFD 2 which builds on the design requirements that were the output of QFD 1. The first step of QFD 2 is to identify engineering characteristics based on the high priority design requirements.

SAD with two lines	Physically larger SAD
Good energetic performance at all temperatures	Use proven energetic material Use liners between materials
Use energetics that degrade slowly	Large stabiliser proportion Select stable energetics
Excess energy from final booster	Directional booster output Larger energetic mass
Minimal energetic material to achieve function	Lower energetic mass

In the same way as the QFD 1 matrix related the customer requirements to the design requirements, the QFD 2 matrix relates the design requirements to the engineering requirements. Only the higher priority design requirements have had engineering requirements generated for them. Like QFD 1, a weighting must be given to each design requirement based on its importance to the overall system prior to creating the QFD 2 matrix.

SAD with two lines	7
Good energetic performance at all temperatures	10
Use energetics that degrade slowly	9
Excess energy from final booster	3
Minimal energetic material to achieve function	3

Using the weighting above, the QFD 2 matrix can be generated. Within the House of Quality matrix, relationships are rated as either strong (9), medium (3), or weak (1). This can be seen in Table 2.

		Design Requirement Weighting	Engineering Requirements							
			Physically larger SAD	Use proven energetic material	Use liners between materials	Large stabiliser proportion	Select stable energetics	Directional booster output	Larger energetic mass	Lower energetic mass
Design Requirements	SAD with two lines	7	9	3	1	1	1	1	3	1
	Good energetic performance at all temperatures	10	1	9	9	3	9	9	3	1
	Use energetics that degrade slowly	9	1	3	1	9	9	1	1	1
	Excess energy from final booster	3	3	3	1	1	1	9	9	1
	Minimal energetic material to achieve function	3	1	9	3	3	3	9	1	9
Engineering Requirement Priority			94	174	118	130	190	160	90	56

Table 2 – QFD 2 to determine engineering requirement priority.

The output of QFD 2 is the engineering requirement priority which tells the author which engineering requirements are the most important for achieving the design requirements inputted into the matrix. For the igniter design, the priorities are thus:

1.	Select stable energetics	190
2.	Use proven energetic material	174
3.	Directional booster output	160
4.	Large stabiliser proportion	130
5.	Use liners between materials	118
6.	Physically bigger SAD	94
7.	Larger energetic mass	90
8.	Lower energetic mass	56

This list tells you which engineering requirements to prioritise to achieve the design requirements necessary. Therefore, this also achieves the customer requirements that were the original input into the QFD process.

The most important engineering requirements are to use proven and stable energetics within the ignition train and the SAD. By contrast, the least important are changing the mass of the energetic components to be greater or lower.

Potential Failure Modes

Analysis potential failure modes highlights where the design may fail or underperform. It also finds noises for which controls can be determined to improve reliability. To do this, the systems engineering process of Failure Modes and Effects Analysis (FMEA) is used.

Functional analysis done earlier in this report found that the following functions were critical to the design of an igniter:

Moving the ignition train into line
Electrically initiating the ignition train
Propagation of initiation through ignition train
Initiation of the main charge

Taking these critical functions, potential failure modes should be identified for them. A failure mode describes how a component or system may fail to perform it's intended function.

Moving the ignition train into line	Arming electrical current is insufficient Moving components may jam
Electrically initiating the ignition train	Firing electrical current is insufficient EBW circuit short circuits
Propagation of initiation through ignition train	Failure of igniter casing Insufficient energy due to temperature Moisture ingress degrading energetics
Initiation of the main charge	Failure of igniter casing Insufficient energy due to temperature Moisture ingress degrading energetics

The next step in FMEA is to determine the effects of each failure mode:

Arming electrical current is insufficient	Solenoid will simply not function leading to the ignition train being broken and unable to work.
Firing electrical current is insufficient	EBW will not generate sufficient thermal energy to ignite/detonate energetic and thus the igniter will not function.
Moving components may jam	Physically rotating components may be unable to move due to interference which will lead to the igniter failing to arm and the ignition train being broken.
EBW circuit short circuits	Electrical current grounds itself and the EBW does not reach a sufficient temperature to initiate energetic.
Failure of igniter casing	Pressure or shock from energetic exploding breaks the casing thus allowing pressure to reduce and energy transmission between energetics to reduce.
Insufficient energy due to temperature	Cold temperatures cause the pressure of energetic ignition/detonation to be lower to the point where it no longer initiates other energetics in the ignition train.
Moisture ingress degrading energetics	Moisture can cause energetic decomposition to be accelerated and thus usable explosive mass to be reduced/damped. Insufficient energy transfer to next stage in ignition train.

Each failure mode needs to also be analysed for root causes and noises. Noises are external factors that could lead to or exacerbate failures.

Arming electrical current is insufficient	Cause	High resistance in arming line due to weather
	Noise	Temperature variations in environment
Firing electrical current is insufficient	Cause	High resistance in firing line due to weather
	Noise	Temperature variations in environment
Moving components may jam	Cause	Poor manufacturing quality
	Noise	Thermal expansion
EBW circuit short circuits	Cause	Physical damage to igniter
	Noise	Moisture ingress
Failure of igniter casing	Cause	Poor quality control
	Noise	Higher than expected pressure gas
Insufficient energy due to temperature	Cause	Cold atmospheric temperatures
	Noise	Design with small design factor
Moisture ingress degrading energetics	Cause	Poor seals on igniter – exposed to atmosphere
	Noise	High humidity local climate

Part of FMEA is to also assess the risk of each failure mode. This involves evaluating the severity, likelihood, and detection of each failure mode. This is assessed on a scale of 1-10 where 10 represents high severity, high likelihood, and high difficulty to detect before the failure causes harm respectively. The Risk Priority Number (RPN) is the product of the multiplication of severity, likelihood, and detection and helps prioritise which failure mode requires the most attention.

Failure Mode	S	L	D	PRN
Arming electrical current is insufficient	3	1	3	9
Firing electrical current is insufficient	3	3	5	45
Moving components may jam	8	2	1	16
EBW circuit short circuits	3	1	3	9
Failure of igniter casing	10	4	1	40
Insufficient energy due to temperature	3	1	7	21
Moisture ingress degrading energetics	10	6	6	360

For each failure, starting with those that have the highest PRN, control measures should be implemented that prevent the failure or detect it early.

Failure Mode	Control
Arming electrical current is insufficient	Semi-regular electrical continuity testing Live feedback to operator on arming status
Firing electrical current is insufficient	Semi-regular electrical continuity testing Live feedback to operator on firing status
Moving components may jam	Prove reliability of moving components through testing Feedback to operator based on sensor
EBW circuit short circuits	Live feedback to operator on firing status Additional physical protection for EBW circuit
Failure of igniter casing	Prove reliability of casing through testing Ensure good quality control during manufacture
Insufficient energy due to temperature	Prove energetic reliability through testing
Moisture ingress degrading energetics	Ensure good quality control on seals at manufacture Frequent visual inspection on igniter/motor seals Leak testing of igniter/motor after manufacture

Now that controls have been identified, the PRN can be recalculated with these controls in mind.

Failure Mode	S	L	D	PRN
Arming electrical current is insufficient	3	1	2	6
Firing electrical current is insufficient	3	2	2	12
Moving components may jam	8	1	1	8
EBW circuit short circuits	3	1	2	6
Failure of igniter casing	10	1	1	10
Insufficient energy due to temperature	3	1	7	21
Moisture ingress degrading energetics	10	2	6	120

This information is often represented within a large table called an FMEA table. By performing an FMEA on the igniter, potential failure modes have been identified and mitigated while the reliability of the design has improved.

Manufacturing Processes Involved

At this point in the development process, manufacturing processes must be considered. Manufacturing processes can be based on the engineering requirements while factoring control measures to mitigate or remove failure modes.

To develop a manufacturing process, the igniter components must be identified. Appropriate manufacturing methods should be selected for each component:

SAD electronics (EBW circuit)	Electronics soldered by hand.
SAD housing	Manufactured by Computer Numerical Control (CNC) machines.
SAD pyrotechnics	Likely gently pressed into SAD housing.
SAD rotary solenoid	Manufactured by CNC machines.
Igniter pyrotechnic	Powder and pellets placed within igniter can.
Igniter pyrogen	EDB pyrogen stick bonded into igniter body.
Igniter can	Manufactured by CNC machines.
Igniter body	Manufactured by CNC machines.
Igniter body rubber lining	Spin lining the igniter body.
Igniter foil	Bonded over igniter nozzle/other openings.

These components would have tolerances applied to them to allow for a degree of variation that is inevitable in manufacturing, but that does not negatively affect the final product. During manufacturing processes, manufacturing areas should be temperature and humidity controlled to ensure precision. This is most important for all the metal housing and body components as they are often intricate items to save weight where additional material is not needed.

All metal components would be inspected using visual inspection methods, instrumentation, or Coordinate Measuring Machines (CMMs). As the electronics will need to have feedback mechanisms to mitigate the impact of several failure modes, these will need to be included and then calibrated. This calibration ensures that they are operating correctly and that they report the expected and correct information.

The order of assembly of the SAD sub-assembly would be to insert the rotary solenoid into the housing, then the pyrotechnics into rotary solenoid. Finally, the EBW circuit will be shunted and then inserted into the sub-assembly. The order of assembly for the igniter would be for the pyrotechnic powder and pellets to be inserted into the igniter can. The igniter body would then be spin lined with a rubber lining material. Once this has set, the pyrogen can be bonded into the body. Finally, the igniter foils can be applied over the nozzle. Once all three sub-assemblies are complete, they can be attached together.

The assemblies will then undergo electrical continuity testing, capacitance testing, and insulation resistance testing. Visual inspection will be done on the assembly to ensure it complies with acceptance specifications. Within each batch, several items will be allocated to be Production Control Rounds (PCR) and will be sent for functional testing. If the results obtained from this are as expected and within specification the batch can be cleared for sale to a customer.

A Process FMEA (PFMEA) may be done to identify issues affecting manufacturing. In this example, it might highlight things such as poor soldering joints which could lead to unreliable connections within the EBW circuit or incomplete coverage of the inside of the igniter body by the rubber insulation which could lead to burn through and failure of the body.

Many tasks can then be optimised for cost and efficiency. For example, simple and repetitive processes may be automated to permit high volumes and consistent results. Lean manufacturing principles can be implemented to minimise waste and improve production throughput.

Critical Process Steps

QFD 3 is the systems engineering tool that focuses on identifying critical process steps that are vital for ensuring the design's quality during manufacturing. QFD 3 relates the critical engineering requirements generated in QFD 2 to manufacturing process steps.

Like QFD 1 and QFD 2, a weighting must be given to each design requirement based on its importance to the overall system prior to creating the QFD 3 matrix.

Redundancy in ignition sources	5
Good performance at all temperatures	7
Slow degrading energetics	7
Excess energy from all energetics	2
Minimal energetic material to achieve function	1

Using the weighting above, the QFD 3 matrix can be generated. Within the House of Quality matrix, relationships are rated as either strong (9), medium (3), or weak (1). This can be seen in Table 3.

		Engineering Requirement Weighting	Manufacturing Process Steps							
			Component manufacturing	SAD sub-assembly	Igniter can sub-assembly	Igniter body sub-assembly	Final assembly	PCR functional testing	Electrical testing	Quality inspection
Engineering Requirements	Redundancy in ignition sources	5	3	9	1	1	1	3	3	1
	Good performance at all temperatures	7	9	1	1	1	1	9	3	1
	Slow degrading energetics	7	9	1	1	1	1	1	1	1
	Excess energy from all energetics	2	9	3	3	3	1	3	1	1
	Minimal energetic material to achieve function	1	9	3	3	3	1	9	1	1
Critical Process Steps			168	68	28	28	22	100	46	22

Table 3 - QFD 3 to determine critical process steps.

The output of QFD 3 is the critical process steps which tells the author which process are most important for achieving the design requirements inputted into the matrix. For the igniter design, the order of process steps from most critical to least is:

1.	Component manufacturing	168
2.	PCR functional testing	100
3.	SAD sub-assembly	68
4.	Electrical testing	46
5.	Igniter can sub-assembly	28
6.	Igniter body sub-assembly	28
7.	Final assembly	22
8.	Quality inspection	22

Made visible by this QFD 3, additional resources should be allocated to component manufacturing to ensure that these critical processes are carried out with precision and accuracy. PCR functional testing is also a critical process that should never be skipped as it proves that igniters are meeting the design requirements. By contrast, quality inspection and final assembly require fewer resources to ensure the product meets the design requirements. This indicates that they do not directly add value to the product and rather fulfil supportive roles in the process.

Process Control Measures

QFD 4 is the last step in the QFD process within which you identify process control measures to ensure that the critical process steps identified in QFD 3 are performed consistently and effectively. The purpose of these controls is to prevent defects and ensure the quality of the final product.

The first step in QFD 4 is to identify key process variables for each process step identified in QFD 3.

Component manufacturing	Temperature control Humidity control Calibrated instruments (e.g., torque wrenches) Soldering temperature Anti-static work area
PCR functional testing	Calibrated instruments (e.g., load cells, pressure transducers) Monitoring with high-speed cameras
SAD sub-assembly	Calibrated instruments (e.g., torque wrenches) Temperature control Humidity control Soldering temperature Anti-static work area
Electrical testing	Temperature control Humidity control Record of resistance of the wires Anti-static work area
Igniter can sub-assembly	Calibrated instruments (e.g., torque wrenches) Temperature control Humidity control Anti-static work area
Igniter body sub-assembly	Calibrated instruments (e.g., torque wrenches) Temperature control

	Humidity control Anti-static work area
Final assembly	Calibrated instruments (e.g., torque wrenches) Temperature control Humidity control
Quality inspection	Temperature control Humidity control

For each key process variable, a process control measure should be used to guarantee the process stays within acceptable limits and tolerances.

Temperature control	Air conditioning in all manufacturing areas
Humidity control	Air conditioning in all manufacturing areas
Calibration of equipment	Local calibration equipment, regular formal calibration
Soldering temperature	Suitable equipment that tells operator the temperature
Anti-static work area	Conductive PPE, conductive floors and benches
Monitoring with high-speed cameras	Installation of high-speed camera in functional test area
Record resistance of wires	Process changes prior to electrical testing

Installation of these process control measures would prevent the process variables from having a negative impact on the quality of the product by improving the manufacturing process area and equipment. Once they have been implemented, their effectiveness should be monitored to guarantee they are achieving their function. Statistical Process Control (SPC) techniques allow trends in data to be analysed and helps identify any deviations or weak signals. When these are identified, action should be taken to prevent them from affecting products. Periodic audits can help maintain the effectiveness of these control measures.

Discussion

As can be seen in the example worked through above, the use of systems engineering tools allows issues to be 'left-shifted'. What this means is that potential problems are found earlier in paper exercises rather than during development where a mistake will cost significantly more and would incur a time delay on the project. By finding the mistakes in design while using systems engineering tools, a better design can be made before committing anything to being manufactured. Likewise, a better manufacturing process can be devised before committing resources in procuring equipment, facilities, or material.

The following list will contain each systems engineering tool used and summarise how it assists the design process:

- QFD 1 – Customer Requirements to Design Requirements
 - Clarifies customer's requirements by converting them into actionable design requirements.
 - Prioritises the design requirements that will best achieve the customer's requirements.
- Functional Analysis
 - Helps to understand the functionality of both the system and sub-systems.
 - Considers all necessary functions during design to ensure completeness of design.
- QFD 2 – Design Requirements to Engineering Requirements
 - This stage maps the customer requirements against actual engineering decisions.

- Helps to prioritise some solutions over others.
- Failure Modes and Effects Analysis (FMEA)
 - Helps identify areas where the design might fail.
 - Helps prioritise the risk of failure of each part of the design.
 - Allows controls to be implemented early in the process of design.
- Manufacturing Process Analysis
 - Helps evaluate the options available for manufacture of the design.
 - Helps to realise the supporting processes for the manufacturing, e.g., testing.
- QFD 3 – Design Requirements to Process Steps
 - Translates design features into manufacturing steps.
 - Helps prioritise resource to more critical manufacturing steps.
- QFD 4 – Process Steps to Control Measures
 - Improves quality assurance by making processes more consistent and produce better product.
 - Establishes process monitoring and SPC techniques to manage trends.

Overall, the effect of using systems engineering tools is to improve customer satisfaction by aligning design, engineering, and manufacturing decisions with the customer's original requirements.

Conclusions

- Systems engineering tools successfully 'left shift' design flaws and allow for them to be addressed at low cost without incurring a delay to the programme.
- Systems engineering tools help structure the development process of new designs in such a way that keeps the design in-line with customer requirements and expectations. Customer satisfaction is achieved this way.

References

- [1] S. B. Joseph Berk, "Quality Function Deployment," in *Quality Management for the Technology Sector*, 2000, p. 124.