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Systems Thinking Design Report

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1. Introduction

Systems Engineering (SE) is a holistic, big-picture approach to designing and managing complex systems and processes. It ensures all components throughout a system's lifecycle work together effectively by overseeing the entire lifecycle, from concept, research and development, in service and disposal [1]. SE within the context of Ordnance, Munitions and Explosives (OME) is a critical factor in ensuring reliability, safety and risk control. This is vital due to the inherent risks involved in producing and operating high-energy, hazardous materials.

This report presents a systems-thinking analysis of a mine detection and clearance system, with a specific focus on manufacturing safety. With the aid of a systems engineering workbook and a preset brief, a design process has been produced, ensuring safety and reliability were embedded throughout the system's lifecycle, whilst also ensuring the key customer requirements were identified and met. The report will evaluate how using the workbook assisted the design process via the identification of the following:

- Key customer requirements.
- Critical system functionality.
- Concept derivation and design choices
- Potential failure modes.
- Critical design features.
- The manufacturing processes involved.
- Critical process steps.
- Process control measures.
- Waste and end-of-life disposal.

The design brief is as follows. A medical supply convoy must pass through a mined desert passage where rerouting and helicopter support are not viable due to the terrain and threat of MANPAD. The mission requires a rapid, road-based solution to detect, clear and mark mines, enabling safe passage for the convoy. There is a restriction on heavy machinery and vehicles, and therefore a customised Land Rover-like vehicle must be used. There is already a constraint on using in-service mine clearance systems, such as Python, due to safety concerns from fragmentation. As a result, the task is to design a portable, effective mine clearance system that can be deployed using lightweight vehicles under time-critical conditions.

2. Systems Engineering Workbook

The SE workbook provided a structured process to follow that supported decisions made from concept through to disposal. The workbook comprises each of the 4 QFD's that must be analysed in SE. The 4 QFD stages are [2]:

- QFD 1 – Translating the customers' desires into technical requirements of what the system must output.
- QFD 2 – Converting technical requirements into specific subsystems and design features.
- QFD 3 – Defining how the product is manufactured and the operations processes.
- QFD 4 – The systems production controls, quality assurance and manufacturing reliability.

3. Customer Requirements Analysis

Understanding customer requirements is essential to ensure the system performs the task the customer needs it to. From the workbook, a set of requirements was identified from the brief, with 8 of them identified as the key requirements and highlighted in green. This can be seen in Figure 1.

The system shall detect buried or surface-laid mines typical of legacy and improvised mine threats.
The system shall render detected mines safe by removal, destruction, or permanent disabling.
The system shall be transportable and operable using light vehicles (Land Rover, Hi-Lux, or equivalent).
The system shall clearly mark mines cleared lanes and boundaries in a way visible to follow-on with light wheeled vehicles
The system shall function in high dust, sand, heat, and vibration conditions without degradation of performance.
The system shall clear the required route length within a time window compatible with urgent medical convoy movement.
The system shall limit blast, fragmentation, and collateral damage within the confined pass.
In the event of malfunction, the system shall default to a safe condition without creating additional hazards.
The system shall be designed to enable safe, compliant breakdown and disposal.
The system shall be effective against a range of mine constructions (metallic, low-metal, pressure-activated).
The system shall allow repeated clearance actions along the route without requiring specialised resupply.
Marking shall be intuitive and understandable to non-military, local civilian drivers.
The system shall minimise the need for personnel exposure in uncleared areas.
The system shall not present a high-value explosive target vulnerable to small arms or fragmentation.
The system shall be manually deployable by small teams without heavy lifting equipment.
The system shall require minimal maintenance and be serviceable in austere conditions.
Components should, where possible, align with commercially available or automotive-grade parts.
The system shall be manufacturable using established industrial processes without reliance on exotic materials.
The design shall identify safety-critical components whose failure could result in undetected mines or unsafe clearance.
Manufacturing processes for critical components shall include defined inspection, tolerance, and test controls.
The system shall be testable under representative environmental and operational conditions.
The system shall detect, neutralise, or remove anti-personnel and anti-vehicle mines along a defined road corridor sufficient for light wheeled vehicles (Land Rover / Toyota class).
The system shall provide a verifiable level of confidence that the cleared route is safe for repeated civilian convoy passage.
The system shall enable clearance operations to begin within hours of arrival at the site, with minimal setup and no heavy infrastructure.

Figure 1 - Customer Requirements

These requirements were then put into a pairwise diagram as shown in Figure 2 to rationalise and understand which requirements are most important. The pairwise diagram compares the requirements directly with each other and uses a scoring system to identify importance [3]. This scoring system can also be seen in Figure 2.

Pairwise comparison of requirements		1	2	3	4	5	6	7	8	9	Calc	Calc
1 = No Preference, Reciprocal = 1 2 = Slight Preference, Reciprocal = 0.5 5 = Preference, Reciprocal = 0.2 9 = Strong preference = 0.11												
	The system shall detect buried or surface-laid mines typical of legacy and improvised mine threats.											
	The system shall render detected mines safe by removal, destruction, or permanent disabling.											
	The system shall be transportable and operable using light vehicles (Land Rover, Hi-Lux, or equivalent).											
	The system shall clearly mark mines cleared lanes and boundaries in a way visible to follow-on with light wheeled vehicles											
	The system shall function in high dust, sand, heat, and vibration conditions without degradation of performance.											
	The system shall clear the required route length within a time window compatible with urgent medical convoy movement.											
	The system shall limit blast, fragmentation, and collateral damage within the confined pass.											
	In the event of malfunction, the system shall default to a safe condition without creating additional hazards.											
	The system shall be designed to enable safe, compliant breakdown and disposal of all system components, including explosive payloads, electronic subsystems and structural elements in accordance with applicable environmental, explosive safety, and hazardous waste regulations at end of life.											
1	The system shall detect buried or surface-laid mines typical of legacy and improvised mine threats.	1	1	2	2	2	5	5	5	9	32	1
2	The system shall render detected mines safe by removal, destruction, or permanent disabling.	1	1	2	2	5	9	5	2	9	36	1
3	The system shall be transportable and operable using light vehicles (Land Rover, Hi-Lux, or equivalent).	0.5	0.5	1	2	5	2	1	5	9	26	1
4	The system shall clearly mark mines cleared lanes and boundaries in a way visible to follow-on with light wheeled vehicles	0.5	0.5	0.5	1	9	5	5	5	5	31.5	1
5	The system shall function in high dust, sand, heat, and vibration conditions without degradation of performance.	0.5	0.2	0.2	0.11	1	0.2	0.5	5	5	12.71	1
6	The system shall clear the required route length within a time window compatible with urgent medical convoy movement.	0.2	0.11	0.5	0.2	5	1	1	2	9	19.01	1
7	The system shall limit blast, fragmentation, and collateral damage within the confined pass.	0.2	0.2	1	0.2	2	1	1	2	1	8.6	1
8	In the event of malfunction, the system shall default to a safe condition without creating additional hazards.	0.2	0.5	0.2	0.2	0.2	0.5	0.5	1	1	4.3	1
9	The system shall be designed to enable safe, compliant breakdown and disposal of all system components, including explosive payloads, electronic subsystems and structural elements in accordance with applicable environmental, explosive safety, and hazardous waste regulations at end of life.	0.11	0.11	0.11	0.2	0.2	0.11	1	1	1	3.84	1
											Row Product	
											nth root of row product	
											Total Normalised	

Figure 2 - Pairwise Diagram

The results of the pairwise comparisons are presented in a bar chart in Figure 3, where it was identified that the system shall render detected mines safe by removal, destruction, or permanent disabling, the system shall detect buried or surface-laid mines typical of legacy and improvised mine threats, and the system shall clearly mark mines cleared lanes and boundaries in a way visible to follow-on with light wheeled vehicles as the most important requirements.

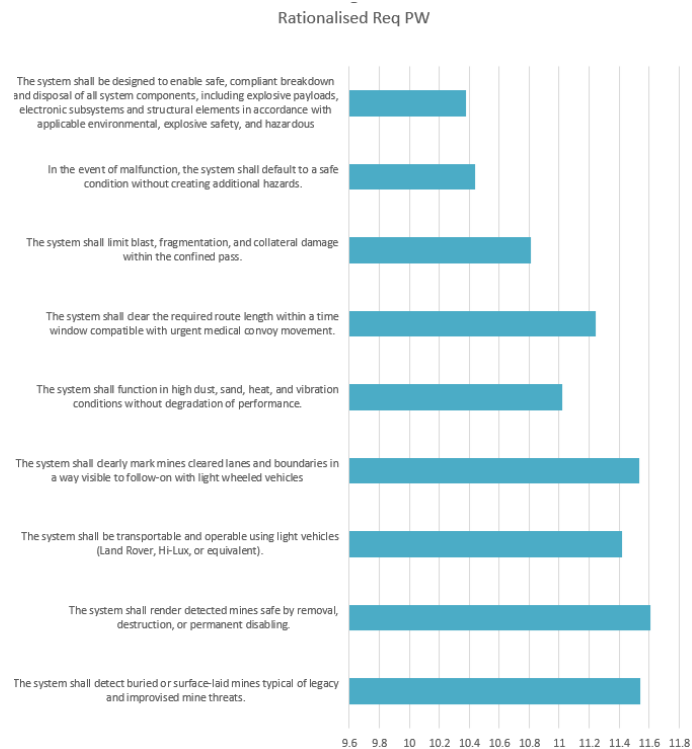


Figure 3 - Requirement Importance Ranking

By using these results, it formed a basis on which all subsequent design features would follow. From a manufacturing safety perspective, this ensured that safety requirements were embedded early and influenced decisions, such as the material of the warhead, which would be reliable to defeat the mines effectively, as the requirement states.

4. Systems Functions Analysis

The next stage was to identify the critical system functions. A critical system function is a part of a system that, if it fails, could jeopardise the ability of the process to flow [4]. By identifying these functions early in the design phase, it ensures that the high-risk functions are prioritised from the start. This reduces the risk of system failure and costly redesigns. Given the nature of the brief, the remote location would prevent spare parts from being easily obtained.

A required functionality was used in the workbook to identify both low-level and high-level functions of the system and can be seen in Figure 4.

Level 1	How Much	Level 2
Deploy Clearance Capability	From Use case	Load off to light Vehicle
		Move to clearance start point
		Online systems and sensors
		Establish exclusion zone
Detect Explosive Hazard		Surface detection
		Subsurface detection
		Noise filtering (rocks, clutter etc)
		Geo-reference detection location
Assess and Decide		Correlate sensor inputs
		Assign confidence level
		Select neutralisation method
Neutralise or Removal		Mechanical disturbance / actuation
		Controlled detonation
Verify Clearance		Extraction or displacement
		Post clearance scan
Mark Cleared Route		Record cleared area
		Define lane width and limits
		Deploy physical markers
Enable Convoy Transit		Deploy visual markers (day / night)
		Lead vehicle convoy
Recover and Redeploy		Clearance integrity monitoring
		Halt / warn if anomaly detected
Render Safe or Dispose of System		Safe stowage of equipment
		Relocate to next identified area
		Deactivation and Neutralisation
		Isolation and Containment
		Dismantling and Disassembly
		Documentation and Certification

Figure 4 - Required Functionality

Following this, a Design QFD 1 could be produced. This compared the key customer requirements against the level 1 functions of the system. Using a 1, 3 and 9 scoring system, it identified the importance of the functions against the customers' requirements. This helps align the requirements and system functions to ensure no requirements are missed when designing the system and avoids design features that do not add value and could become a nuisance in the system. The design QFD 1 is shown in Figure 5, with the results in Figure 6 in the form of a functional importance graph.

How	Importance	Deploy Clearance Capability	Detect Explosive Hazard	Assess and Decide	Neutralise or Removal	Verify Clearance	Mark Cleared Route	Enable Convoy Transit	Recover and Redeploy	Render Safe or Dispose of System
Requirements										
The system shall detect buried or surface-laid mines typical of legacy and improvised mine threats.	11.5415974	3	9	3		9		9	1	
The system shall render detected mines safe by removal, destruction, or permanent disabling.	11.6097681	1	3	9	9			3	3	1
The system shall be transportable and operable using light vehicles (Land Rover, Hi-Lux, or equivalent).	11.4223927	9						9	1	
The system shall clearly mark mines cleared lanes and boundaries in a way visible to follow-on with light wheeled vehicles	11.5325129	1	3	9	1	3	9	9	3	
The system shall function in high dust, sand, heat, and vibration conditions without degradation of performance.	11.0208654	1	9	3	3	9	3	3	1	1
The system shall clear the required route length within a time window compatible with urgent medical convoy movement.	11.24495	1	3		9	3	3	9	9	
The system shall limit blast, fragmentation, and collateral damage within the confined pass.	10.8077016	1			9					
In the event of malfunction, the system shall default to a safe condition without creating additional hazards.	10.4395516			1	3		1	1	3	9
The system shall be designed to enable safe, compliant breakdown and disposal of all system components, including explosive payloads, electronic subsystems and structural elements in accordance with applicable environmental, explosive safety, and hazardous waste regulations at end of life.	10.3806604				1			1	3	9

Figure 5 - Design QFD 1

QFD 1 Functional Importances

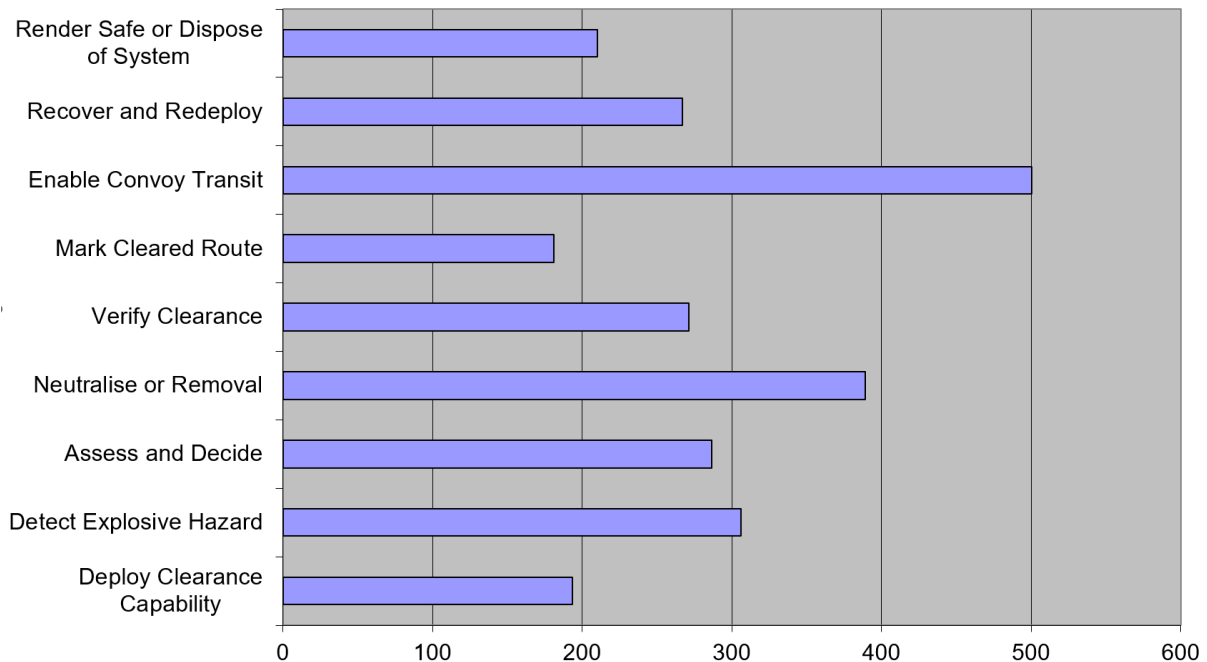


Figure 6 - QFD 1 Functional Importance

As shown in Figure 6, the most important function identified was enabling the convoy to transit, with the ability of the system to neutralise or remove the mine as the second most important function. With neutralise/remove being the second most important feature, it meant that when focusing on the safety of manufacturing, there were clear quality assurance steps to be adhered

to, ensuring that the quality and performance of the final product were not hampered by shortcuts taken during production.

Once this was identified, a Functional Means Analysis could be produced. A Function Means Analysis (FMA) is a structured method for generating, comparing and documenting design concepts. It maps each system function and how this function can be achieved in different ways. Presenting options side by side for each function, it allows for an easy process of elimination on design ideas. Figure 7 shows the produced FMA with red boxes showing options deemed not appropriate, orange as could be used and green as the preferred method.

Function	Means (PRE-PUGH OPTIONS)																	
Deploy Clearance Capability	Drone	Man Portable	Unmanned Ground Vehicle (UGV)	Vehicle Mounted	Split Assembly	Animal Mounted												
Detect Explosive Hazard	Magnetometer	LIDAR	Ground Penetrating Radar	AI	Explosive Sniffing Animal	Crystal Ball	Tarot Cards	Foot Tapping	Prodding	Visuals								
Assess and Decide	AI	Visual		Aide Memoire	Call a Friend	50/50	Ask the Audience											
Neutralise or Removal	Explosive effector	Rifle fire	Distruptor	Laser	Seismic disturbance	Foot tapping	EOD	Don't	Plow	Grapple and hook	Goats	Python	UGV	Dropper drone	Suicide drone	Drone delivered	Force of Nature	
Verify Clearance	Visual	Repeat scan	Send it	Don't	AI	UGV	Explosive Sniffing Animal	Trained Personnel										
Mark Cleared Route	Flag	Paint	Rope / String	Glow Stick	Breadcrumbs	Rocks / sticks / Environment	Barriers	Solar powered lights	Reflective markers									
Enable Convoy Transit	4x4 / Hilux / Defender	Tank	HGV	Sand bags	Digger	Tarmac	Plow	Steam roller	Concrete	Planks of wood	Railway	Helicopter	Clear new path	Mesh road				
Recover and Redeploy	Spare / replaceable parts	Fibre optic	Tow bar	Trailer	Return to home system	Self destruct	Bubble wrap	Big magnet	Fishing rod / Grapple hook									
Render Safe or Dispose of System	Modular	Compliant with Legislation	Non-Hazardous Materials	Safe Shutdown	Self Destruct	Plant Based system	Biodegradable	fly tip										

Figure 7 - Function Means Analysis

5. Concept Development and Design Choices

Using the FMA in Figure 7, three design ideas were created.

- Solution 1 (Animals) - Sniffer animal and human digging out mine to disarm/charge disarm.
- Solution 2 (Drone) - A drone that has a detection system mounted, scans a programmed route, marks out mines, and places charges that defeat mines.
- Solution 3 (Metal detector) - Human goes and walks around to scan, uses a grapple hook to trigger mines.

These 3 solutions were inserted into a Systems Pugh diagram alongside the in-service option Python. The idea of a System Pugh diagram is to compare the 3 designs and how they would perform against the customers' requirements when compared to a baseline design, in this case, Python. The scoring system works where all Python scores will be 0, and the 3 designs are scored with -1 = worse, 0=same, 1 = better and 2 = considerably better.

		Relative Importance Equal	Relative Importance Weighted	Solution 1 (Python)	Solution 2 (Animals)	Solution 3 (Drone)	Solution 4 (Metal Detector)
WHATs - Customer Requirements	How much:- From QFD 1						
The system shall detect buried or surface-laid mines typical of legacy and improvised mine threats.		1	11.54159738	0	1	2	1
The system shall render detected mines safe by removal, destruction, or permanent disabling.		1	11.60976813	0	-1	0	-1
The system shall be transportable and operable using light vehicles (Land Rover, Hi-Lux, or equivalent).		1	11.42239274	0	2	1	2
The system shall clearly mark mines cleared lanes and boundaries in a way visible to follow-on with light wheeled vehicles		1	11.53251289	0	1	2	1
The system shall function in high dust, sand, heat, and vibration conditions without degradation of performance.		1	11.02086541	0	-1	0	-1
The system shall clear the required route length within a time window compatible with urgent medical convoy movement.		1	11.24494995	0	-1	-1	-1
The system shall limit blast, fragmentation, and collateral damage within the confined pass.		1	10.80770156	0	2	2	2
In the event of malfunction, the system shall default to a safe condition without creating additional hazards.		1	10.43955157	0	-1	1	2
The system shall be designed to enable safe, compliant breakdown and disposal of all system components, including explosive payloads, electronic subsystems and structural elements in accordance with applicable environmental, explosive safety, and hazardous waste regulations at end of life.		1	10.38066037	0	0	2	1
				0	2	9	6

Figure 8 - Systems Pugh Diagram

As shown in Figure 8, the drone solution was by far the most effective with an overall score of 9. Following this result, it was decided to use this solution and finish the rest of the workbook around this design.

The next stage was to use the design features identified in the FMA and understand the importance of these features compared to the previously identified key system functions. This is known as QFD Design 2 and can be seen in Figure 8. The scoring system followed the same process as QFD 1 and produced results clearly indicating which design features were most important.

Design feature	Importance	Importance	Drone	UGV	4x4 Mounted	Split Assembly	Ground Penetrating Radar	AI	Visual	Trained Personnel / EOD	Aide Memoire	Explosive Effector	Repeat Scans	Flags / Reflective Markers	Sand Bags	Plow	Spare / Replaceable Parts	Tow Bar / Trailer	Return To Home System	Modular	Compliant with Legislation	Non-Hazardous Materials	Safe Shutdown
Functionality																							
Deploy Clearance Capability	194	10	19.364212	9	9	9	9			3							9	9	3	9			
Detect Explosive Hazard	306	10	30.622386	3	1			9	3	3	3	3		9			1						3
Assess and Decide	286	10	28.640747	1				9	9	3	9	9		3			1						
Neutralise or Removal	389	10	38.92562	3	1					3	3	9	9			3	1						
Verify Clearance	271	10	27.139455	1	9			9	9	3	3	1	1	9			1						
Mark Cleared Route	181	10	18.102961		9			3	1	1	3			1	9		1					9	
Enable Convoy Transit	500	10	50.038519		3	3	1	1		1	3		3	3	9	9	9	1	1				
Recover and Redeploy	267	10	26.707688	9	3	3	9			3				3	3	3	9	9	9	9		1	3
Render Safe or Dispose of System	210	10	21.001254														9		9	9	3	9	9
			679	881	405	465	882	612	444	890	727	528	774	693	530	647	797	465	487	604	63	379	361

Figure 9 - Design QFD 2

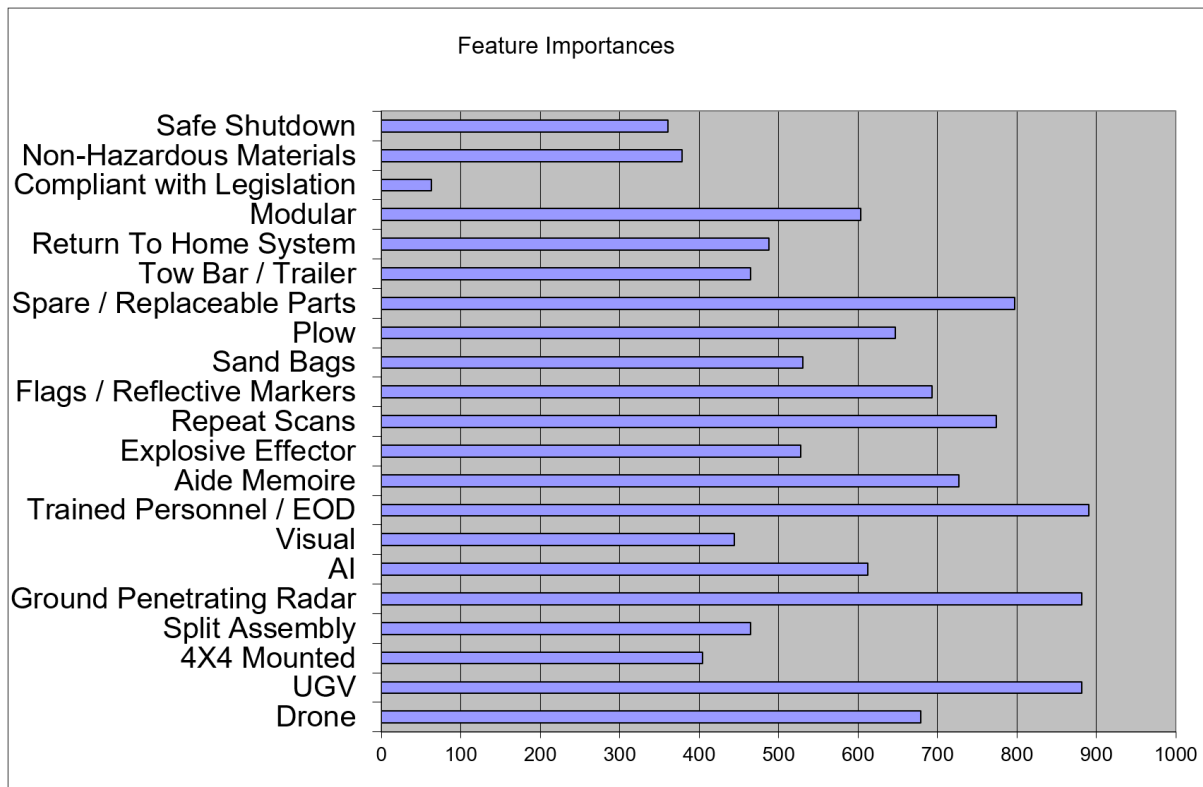


Figure 10 - Design Feature Importance

Figure 10 shows the results from Figure 9 in a feature importance chart. It was identified that the 3 main features of our design would be the use of a commercial off-the-shelf (COTS) UGV to identify and plough a safe path, a ground penetrating radar (GPR) for the drone to identify the landmines and the attendance of trained Explosive Ordnance Disposal staff to ensure tasks were carried out correctly and safely.

From here, concept designs were produced to create a visual aid for the design. The concepts can be seen in Figure 11, showing a drone using a shaped charge to defeat the landmine as well as a GPR for detection. It was decided to use a shaped charge due to its great penetration ability from a small, easily transferable object to help usability and logistics.



Figure 11 - Drone Concepts

A key part of QFD 2 is understanding the noise and control factors of the system. Noises are variables that can affect the system; they're not always easy to control and add uncertainty to the process. Noises come in 3 forms: unit-to-unit, which refers to variations between manufacturing processes and operators, external noises are variables from the operating environment, and deterioration noises are variables that come due to fatigue and ageing. Control factors can be controlled and are implemented to optimise performance, quality and cost [5]. To understand and identify the noises and controls of the GPR drone system in its real-world operating conditions, a P diagram has been created and illustrated in Figure 12. This diagram helps to identify potential noises the system will encounter and how to ensure the system is robust enough to overcome these issues.

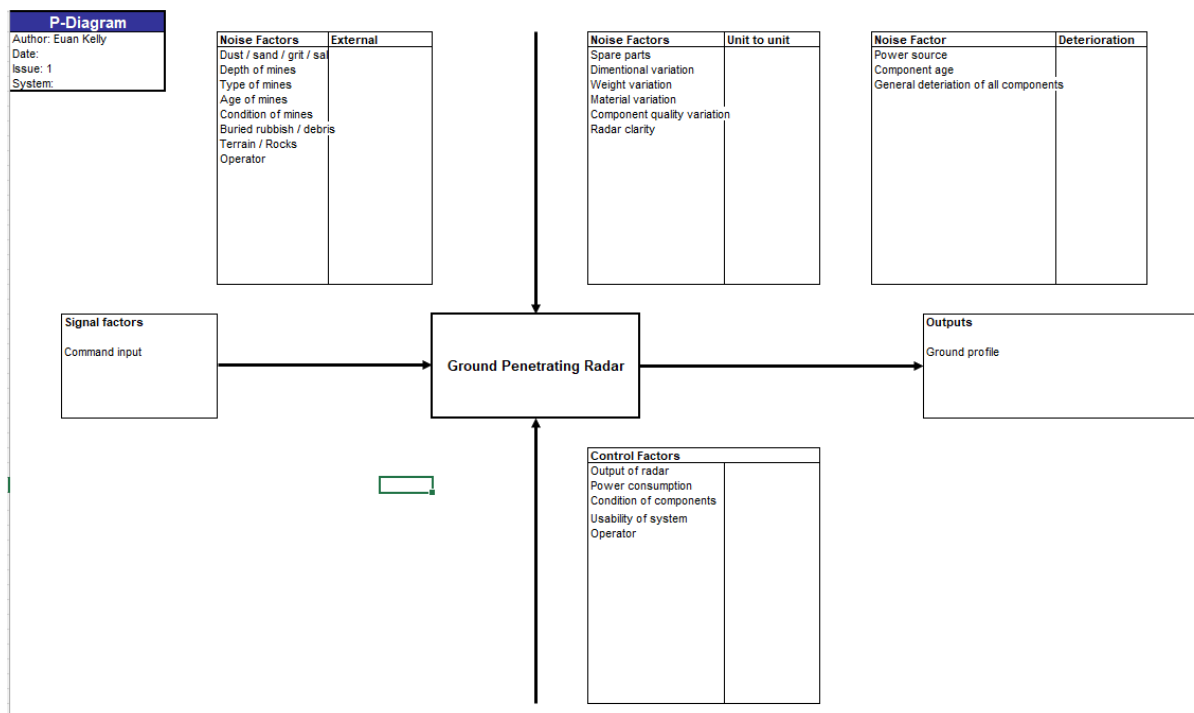


Figure 12 - GPR P Diagram

Following the identification of the controls and noises, a what-why diagram could be produced. A what-why diagram compares the design controls against the noises using the same scoring method as QFD 1 & 2. This helps identify the key controls and noises of the system.

		NOISE FACTORS																
Design control parameters	Weighting of design control parameter	Unit to Unit Variation					Deterioration			External							Human	Total
		Mfg					Raw Mat'l			Environment								
		Spare parts variation	Dimensional variation	Weight variation	Material variation	Component quality variation	Radar clarity	Power source	Component age	General deterioration of all components	Dust / sand / grit / salt	Depth of mines	Type of mines	Age of mines	Condition of mines	Buried rubbish / debris	Terrain / Rocks	
Output of radar	4	1				1	9	3	3	3	3	9	1		1	1	3	38
Power consumption	1	9		1	1	1	1	9	9	3		3					1	38
Condition of components	5	3				9	9	1	9	9	9						1	50
Usability of system	3		1	1	1		3	9	1	3	3						9	31
Radar operation	2		1	1	1	3	3	3	3	3	3	3	1		1	1	3	39
																		0
																		0
																		0
																		0
																		0
Relative importance of noise factor:		28	5	6	6	56	97	59	75	75	72	45	6	0	6	6	18	51

Figure 13 - What-Why GPR System

The resulting values indicated that the biggest noise factors for each type are radar clarity in unit to unit, general deterioration, and age for deterioration factors and finally dust/sand/grit/salt for the external noises. The most important controls were the condition of components and the output of the radar.

6. Failure Modes and Risk Analysis

It was necessary to complete a Failure Modes and Effects Analysis (FMEA) for this system. This method is used to identify, assess and reduce potential failures. Failure modes are how something in the system could fail, effects are what happens if this fails, and the causes are what would make this part of the system fail. Each risk is evaluated independently using severity, likelihood, and detectability to help identify and prioritise the most critical issues more easily [6]. FMEA are highly useful in identifying risk and failures, but it does not, however, capture any unexpected failures of the system and therefore it is important to note that a system will not be immune to failure purely because an FMEA has been completed.

Throughout this workbook, 2 FMEA's were completed, one for the Test and Evaluation (T&E) process and another for the safety during operation. The biggest risk is identified by the RPN number, which is calculated by multiplying the severity, likelihood and detectability. For T&E, the highest scoring RPN was the Inability to consistently identify the same threat signatures, which was by far the largest score. Once the risk has been identified, a safety mitigation can be put in place. In this case, it was decided to use inert mines in training until confidence could be confirmed in both the operator and the system's ability, where live explosives could then be introduced to confirm the detectability of the mines effectively.

Effect	S (1-10)	Cause	O (1-10)	D (1-10)	RPN	Safety Mitigations	Keys
No information available on performance in mechanical and climatic environment	6	Malfunction of the test kit / Omission from trials schedule	1	1	6		1 No function
Excessive degradation of equipment and failure of the trial - hardware damage	7	Malfunction of the test kit / Human error during trial set-up	2	4	56		2 Too much function
Equipment under-tested - failure of trial	6	Malfunction of the test kit / Human error during trial set-up	3	4	72		3 Not enough function
Reliability of results questioned - failure of trial	5	Malfunction of the test kit / Human error during trial set-up	2	6	48		4 Intermittent function
Reliability of results questioned - failure of trial	5	Pre-trial malfunction	1	2	10		5 Unintended function
Unusable system	4	Insufficient training data or poor software design	3	1	36		
Pulse alarms identified as threats - inefficient system	9	Insufficient training data or poor software design	3	6	48		
Real threats missed - present a danger in operational field	9	Insufficient training data or poor software design	3	6	48		
Potential to miss real threats - present a danger in the operational field	9	Insufficient training data or poor software design	3	6	48		
Operational noise in the presence of personnel not under control	10	Poor hardware or software design / Human error - inadvertent turning on of radar	3	6	108		
No radar detected - area remains mined	9	Human error / poor command / insufficient training data or poor software or hardware design / hardware damage	1	1	9		
2a. Time wasted dealing with false positives 2b. potential initiation of ordinance	2a, 4 2b, 10	Insufficient training data or poor software design / hardware damage / poor hardware design	2a, 3 2b, 2	2a, 3 2b, 10	2a, 36, 2b, 200		
Dangerous ordinance remains unknown to operators	9	Human error / poor command / insufficient training data or poor software design / hardware damage / poor hardware design	3	3	81		
Operators lack clarity on safety of the operational area	9	Human error / poor command / insufficient training data or poor software design / hardware damage / poor hardware design	3	3	81		
Potential RF exposure to personnel	10	Human error / poor command / poor software design / hardware damage / poor hardware design	3	10	300		
No information available on performance in mechanical and climatic environment	6	Malfunction of the test kit / Omission from trials schedule	1	1	6		
Excessive degradation of equipment and failure of the trial	7	Malfunction of the test kit / Human error during trial set-up	2	4	56		
Equipment under-tested - failure of trial	6	Malfunction of the test kit / Human error during trial set-up	3	4	72		
Reliability of results questioned - failure of trial	5	Malfunction of the test kit / Human error during trial set-up	2	6	48		
Reliability of results questioned - failure of trial	5	Pre-trial malfunction	1	2	10		
Payload not delivered to target	8	Insufficient IIR capability / deploying mechanism failure / reliability / human error	4	1	32		
Potential impact on disrupting target / potential damage or destruction of payload in operational field	7	Insufficient IIR capability / deploying mechanism failure / reliability	2	4	56		
Potential impact on disrupting target / unstable placement of charge	8	Deploying mechanism failure	4	4	128		
Uncertain outcome of delivery system	7	Deploying mechanism failure / inaccurate charge mass / human error / deploying mechanism failure	4	6	168		
Payload dropped either before or during drop travel	5	Deploying mechanism failure / insufficient IIR capability / human error	3	5	75		
Charge deemed not suitable for use UNO	9	Poor explosives manufacturing / insufficient explosives train / supporting equipment malfunction / human error	3	6	162		
Charge deemed not suitable for use UNO	9	Out of date charge / human error / unsuitable environment	2	6	108		
Insufficient damage	5	Out of date charge / human error / unsuitable environment / insufficient explosives train	4	7	242		
Partial detonation / potential misfires	9	Out of date charge / supporting equipment malfunction / human error / poor explosives manufacturing	4	7	282		
Danger to personnel operating equipment / danger in storage	10	Out of date charge / supporting equipment malfunction / human error / poor explosives manufacturing	2	10	200		
Large UNO on top or target / misused mine left behind	9	Poor explosives manufacturing / insufficient explosives train / supporting equipment malfunction / human error	3	6	162		
Waste hazard damage / potential sympathetic detonation in operational field	9	Out of date charge / human error	2	7	126		
Waste hazard damage / potential sympathetic detonation in operational field	9	Out of date charge / human error / insufficient explosives train	3	9	243		
Only some charges have desired effect	9	Inconsistent manufacturing / human error in set up / Out of date charge / supporting equipment malfunction	3	4	108		
One or both explosives devices function without intention or warning posing danger to personnel	10	Out of date charge / supporting equipment malfunction / human error / poor explosives manufacturing	3	10	300		
No information available on performance in mechanical and climatic environment	6	Malfunction of the test kit / Omission from trials schedule	1	1	6		
Excessive degradation of equipment and failure of the trial	7	Malfunction of the test kit / Human error during trial set-up	2	4	56		
Equipment under-tested - failure of trial	6	Malfunction of the test kit / Human error during trial set-up	3	4	72		
Reliability of results questioned - failure of trial	5	Malfunction of the test kit / Human error during trial set-up	2	6	48		
Reliability of results questioned - failure of trial	5	Pre-trial malfunction	1	2	10		
Intended effect not delivered	6	Poor manufacturing / UVG failure / ground too solid	2	1	12		
Chit and round will be larger than intended	2	Bad design / UVG moves too quickly	2	1	12		
Chit and round will be larger than intended	4	Under-powered UVG / poor manufacturing / bad design	4	3	48		
Boundary along cleared route will be inconsistent	5	Poor manufacturing	4	2	48		
UVG creates chit and round when it should not making the cleared area harder to traverse	5	Poor design of UVG / system	2	1	10		
System unable to operate in intended environment	6	Unusable vehicle / poor build quality	3	6	144		
System may fail when suitable for intended environment	5	Poor trial design	1	1	5		
System may not be suitable for intended environment	4	Poor build quality / unusable vehicle /	2	3	24		
System unusable in intended environment	5	Poor build quality / unusable vehicle /	4	5	100		
Test equipment will not take action due to its combined received	8	Poor hardware design / poor system design	3	4	96		
Drone/UVG will take unwanted actions beyond what was ordered	7	Poor hardware design	2	4	56		
Drone/UVG will fail to complete the action	4	Poor software design	3	4	48		
Drone/UVG will be unavailable in the field	7	Poor hardware design	4	5	140		
Drone/UVG will be unavailable in the field	6	Poor software design	1	6	36		
UNO remains / environmental impact	9	Poor explosives manufacturing / insufficient explosives train / supporting equipment malfunction / human error	3	4	108		
Potential damage / training	5	Out of date charge / human error	4	4	96		
UNO system / higher hazard	9	Out of date charge / human error / insufficient explosives train	4	4	144		
UNO system / higher hazard	5	Inconsistent manufacturing / human error in set up / Out of date charge / inconsistent environmental modification	1	2	42		

Figure 14 - T&E FMEA

7. Manufacturing Process Analysis

The manufacturing aspect of this system began with identifying the requirements of manufacturing as well as the processes involved. This can be seen in Figures 15 and 16.

Manufacturing

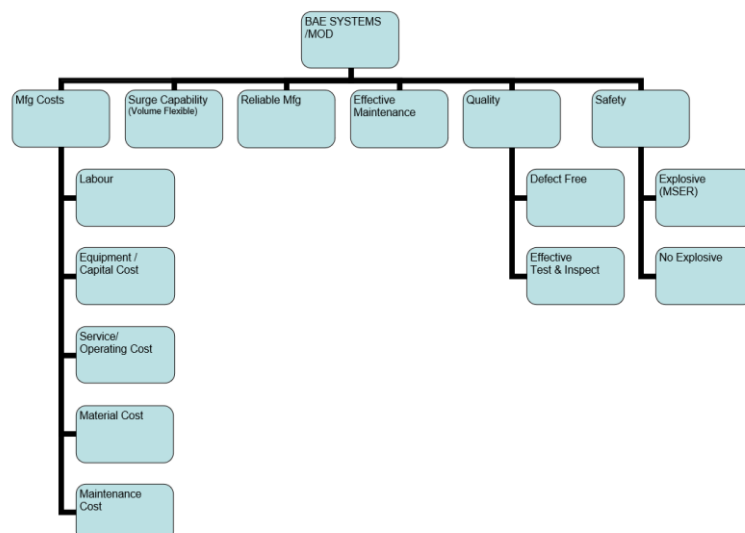


Figure 15 - Manufacturing Requirements

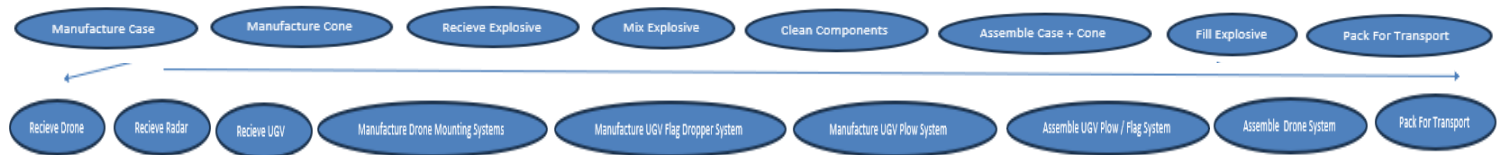


Figure 16 - Process Map

By using Figures 15 & 16, we can repeat QFD 1 on a manufacturing-focused basis to identify the key processes. Figure 17 illustrates this with the results in Figure 18.

Manufacturing Functionality	Importance	Manufacture Case	Manufacture Cone	Recieve Explosive	Mix Explosive	Clean Case / Cone	Assemble Case / Cone	Fill Explosive	Pack Shaped Charge For Transport	Receive Drone	Receive Radar	Receive UGV	Receive Plow	Manufacture Drone Mounting Systems	Manufacture UGV Plow Mounting System	Assemble UGV Plow System	Assemble Drone System	Pack For Transport
Manufacturing Requirements																		
Manufacturing Costs																		
Labour	5	3	3	1	9	3	3	9	3	1	1	1	1	9	9	9	9	3
Equipment capital cost	5	9	9		9		3	9	1					9	9	3	3	3
Service / Operating Cost	5	3	3	1	9	1	1	9	1	1	1	1	1	9	9	3	3	1
Set up cost	5	9	9	1	9	1	3	9	1	1	1	1	1	9	9	3	3	3
Material Cost - Metal Bits	5	9	9						1				9	9	9	1	1	1
Material Cost - Energetic Bits	5			9	9													
Material Cost - other	5					1				9	9	9						
Maintenance Cost		9	9		9	3	3	9	1					3	3	3	3	1
Manufacturing Capacity	5																	
Target production rate XX per month	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Reliable Manufacture	5																	
Repeatable performance	5	9	9	9	3	9	9	3	9	3	3	3	3	3	3	3	3	9
Effective Maintenance	5	9	9		9	1	3	9	3					3	3	3	3	1
Low system outage	5	3	3	1	1	9	3	1	9	1	1	1	1	3	3	3	3	9
Quality	5																	
Defect Free	5	3	3	9	9	9	9	9	9	9	9	9	9	3	3	9	9	9
Effective test and inspection	5	3	3	9	9	3	3	9	3	9	9	9	9	9	9	9	9	3
Safety	5																	
Explosive	5			9	9			9	9							9	9	9
Non-Explosive	5	9	9			9	9			9	9	9	9	9	9			
	5																	
	5																	
	5																	
	5																	
	5																	
		360	360	260	440	245	245	395	260	230	230	230	230	390	390	290	290	270

Figure 17 - QFD 1 Manufacturing Specific

Process Importances Chart

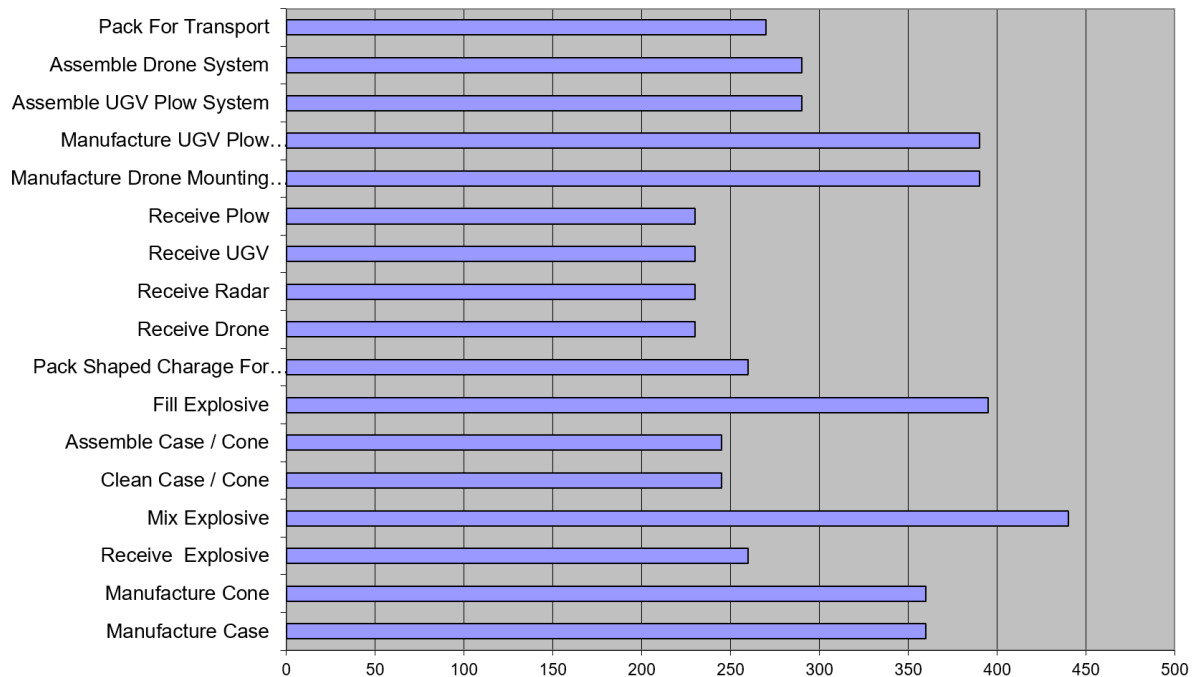


Figure 18 - Process Importance of Manufacturing

As the explosives for the shaped charge are to be manufactured in-house, the most important process was identified as mixing the explosive. This is due to the scoring of 9 for most of the requirements identified.

Identical to the design QFD 1 & 2, this has been repeated for manufacturing using FMA, Systems Pugh and QFD 2, identifying the importance of features compared to the function of the system. This can be seen in Appendix A. It was concluded that the in-house manufacturing would consist of manufacturing the following:

- Shaped Charge Casing
- Shaped Charge Cone
- Explosive Fill
- Bespoke mounting brackets for the interface of the GPR and the shaped charge on the drone
- Bespoke mounting brackets for the UGV plough.

Using the FMA shown in Appendix A, the methods of manufacturing have been compared in relation to the design features through QFD 3. This is shown in Figure 19.

Process Features								
			Importance	3D Printing	Hand Picking	Mixing Bowl	Manual Assembly	Chemical Washing
Important design features								
Shaped Charge Case	50	10	3	9			9	9
Shaped Charge Cone	50	10	2	9			9	3
Explosive Fill	50	10	3		9	9		3
Mounting Brackets For Drone	50	10	3	9			9	
Mounting Brackets For UGV	50	10	3	9			9	
	50	10	3					
	50	10	3					
	50	10	3					
	50	10	3					
	50	10	5					
	50	10	3					
	50	10	5					
	50	10						
				99	27	27	99	42

Figure 19 - QFD 3 Manufacturing

The purpose of QFD 3 is to understand which process techniques are the most important. It was identified that Manual assembly and 3D printing were the most important stages of manufacturing due to the strong links to the design features. However, it is important to note that this is not always the most reliable answer, as one of the most important customer requirements identified was to defeat the mine, which cannot be achieved unless the explosive fill has been mixed in the mixing bowl, and therefore, the answer is slightly conflicting.

7.1 Safety of Manufacturing

Ensuring the workplace is safe during manufacturing is always essential, especially in a scenario where energetic and hazardous substances are in use. Key legislation must be strictly followed in manufacturing; failure to do so puts lives at risk both at the manufacturing stage and in operation, as the quality of a product may alter the performance output. In addition to this, failure to follow legislation can result in the Health and Safety Executive (HSE) shutting down the plant, ultimately resulting in no system being produced to achieve the brief [7].

To ensure the safety of manufacturing explosives, a P diagram has been produced to identify the key noises and controls. This is shown in Figure 20.

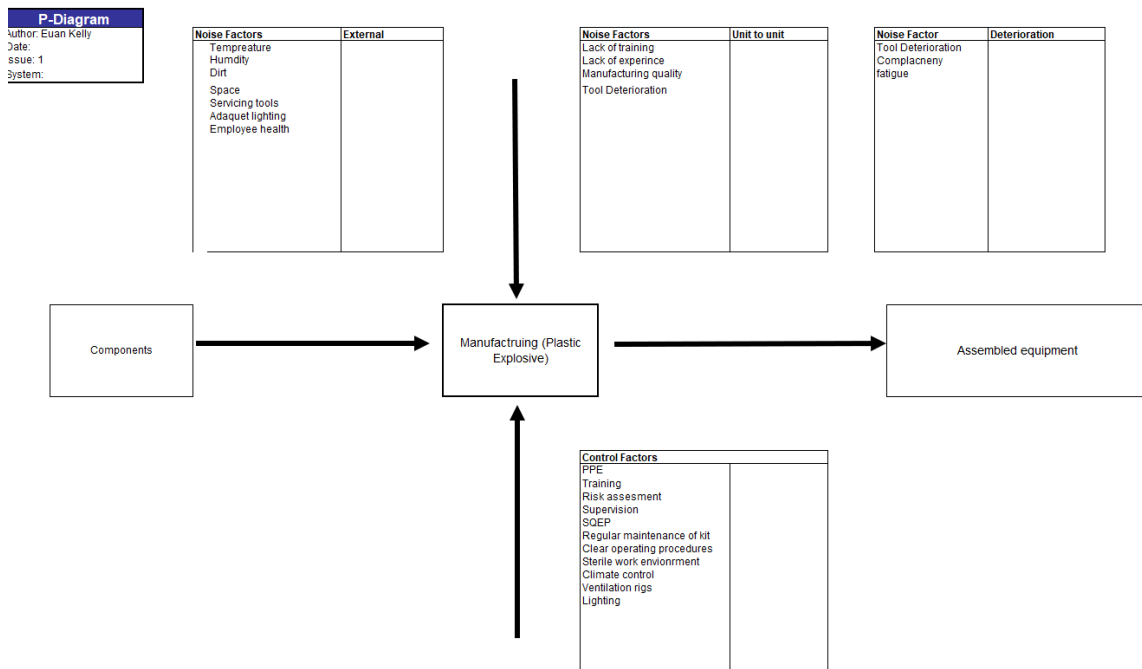


Figure 20 – Manufacturing Plastic Explosive P Diagram

As Figure 20 shows, the noise factors identified with manufacturing plastic explosive were:

External Noises

- Temperature
- Humidity
- Dirt
- Space
- Adequate Lighting
- Employee Health

Unit-to-Unit Noises

- Lack of Training
- Lack of Experience
- Quality of Manufactured Products
- Tool Deterioration

Deterioration Noises

- Tool Deterioration
- Complacency
- Fatigue

The control factors identified were, in this case, heavily influenced by existing legislation in place for facilities and personnel manufacturing explosives. The controls identified were:

- PPE
- Risk Assessments
- Training
- Supervision
- SQEP
- Regular Maintenance of Tools/Machinery
- Clear Operating Procedures
- Sterile Work Environment
- Climate Control
- Adequate Ventilation
- Appropriate Lighting

The controls were identified by reviewing key pieces of legislation, such as the Explosives Safety Regulations 2014, which specifically state that the protection of workers, the public, and infrastructure must be present, as well as proper storage of explosives [8]. The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002 mandate ventilation and explosive prevention measures to be in place with the appropriate PPE and ATEX-rated equipment, including light systems [9]. It is also a legal requirement to follow the Control of Substances Hazardous to Health Regulations (COSHH) 2002 [10] and the Health and Safety at Work Act 1974 [11], which are both governed by the HSE. Both legislations call out the use of proper PPE, training and maintenance of equipment and workspaces.

The controls and noises were once again put into a what-why diagram to fully understand the importance of each control and which noises will be most influential on the system.

Performance Characteristics Ys:	Design control parameters	Weighting of design control parameter	Unit to Unit Variation															Deterioration				External							Relative importance of noise in meeting performance via control factor	
			Mfg																	Environment		Human						Total		
		Lack of Training	Lack of Experience	manufacturing quality	Tool deterioration											Tool deterioration	Complacency	Fatigue				Temperature	Humidity	Space	Dirt	Servicing tools	Adequet lighting	Emplooye Health		
	PPE	2			3												3					3			1			3	13	26
	Training	5	3		3	3										3	3	1						1	3	3		3	50	250
	Risk assesment	2	1	1													3	3	3			3	3	1	1	3	3	3	31	62
	Supension	4	3	3	3	1										1	3	3								3		3	36	140
	SQEP	3	3	3	3	1										1	3	1										3	39	117
	Regular maintenance of kit	5				3	3	3								3	1									3		3	40	200
	Clear operating procedures	4	3	3	3	1										1	3	3				1	1	1	1			3	36	144
	Sterile work environment	1															1	1	1			1	1	3			1	3	26	26
	Climate control	2			3	1										1	3	3				3	3		1			3	33	66
	Ventilation equipment	2			3												3	3				3	3		1			3	25	50
	Lighting	2			3	1										1	3	3						1		3		3	24	48
Relative importance of noise factor:			122	77	183	75	0	0	0	0	0	0	0	0	0	75	138	57	0	0	0	41	47	22	36	141	7	108	0	0

Figure 21 - Manufacturing What-Why Diagram

The formal results of the manufacturing what-why are shown in Appendix B.

From analysing the results of the manufacturing what-why diagram, it is evident that the quality of the manufactured product is the most critical variable to monitor. This is due to the nature of the product and the potential harm it may cause to the end user. Variations in product quality can lead to unreliable or unpredictable performance between units, increasing risk and potentially delaying operations. For example, inconsistencies in detonation pressure within the explosive material may affect the formation of a shaped charge, reduce the effectiveness and potentially prevent the mine from being neutralised.

The what-why results showed the most important control was training. This aligns with the key legislation, stated as ensuring staff are trained and qualified for their role implies that safety-related incidents will be less frequent due to their increased awareness of the hazards. In addition, training will in hand allow for a consistent quality of item to be produced as the staff will understand processes taught in training, directly linking to the key noise identified. Regular maintenance of manufacturing tools was another high-scoring control identified, which also directly links to the quality of products produced, as if tools are breaking or not calibrated correctly, the quality will not be consistent.

Overall, the safety of manufacturing has a clear role and importance throughout the product's lifecycle. It protects both the manufacturers, logistics team and end user whilst also ensuring the quality of the products is maintained and can meet the key customer requirements.

8. Conclusion

This report has demonstrated how a systems engineering approach can be applied to the design of a mine detection and clearance system. Using the systems engineering workbook provided, key customer requirements, critical system functions and appropriate design concepts were systematically identified and evaluated. The application of system engineering tools throughout, such as QFD's, FMA's, Systems Pugh, FMEA and What-whys, enabled justifiable and effective decision-making throughout the process.

The selected concept of a drone able to detect and defeat mines with GPR and shaped charges was deemed the most effective to meet customer requirements under the constraints of the design brief. Safety considerations were made throughout the process, particularly the manufacturing stage, to ensure key requirements were met whilst maintaining the performance of the shaped staff and the health and well-being of specific stakeholders.

The specific focus on manufacturing safety identified the importance of quality control and equipment maintenance, which can all be met through effective training, the highest-level control factor identified.

Overall, this report demonstrates that embedding key systems engineering principles from the start of a system design through to the end enables the development of reliable, safe and effective solutions that meet both operational and regulatory requirements.

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Appendices

Appendix A

Function	Means						
Manufacture Case	Forge	Lathe	Bar Stock	Round Stock	3D Print	Outsourced Case	
Manufacture Cone	Forge	Lathe	Bar Stock	Round Stock	3D Print	Outsourced Cone	
Receive Explosive	Pre-Mixed	Made In House	Outsourced Complete Shaped Charge				
Mix Explosive	Mixing Bowl	RAM	Pre-Mixed	Don't Mix	Made In House	Outsourced Explosive	Outsourced Complete Shaped Charge
Clean Case / Cone	Heat	Chemical Wash	Spit & Shine	Sand / Glass Blast	Polish and Buff	Outsourced Complete Shaped Charge	
Assemble Shaped Charge	By Hand	By Machine	Automated	Outsourced Complete Shaped Charge			
Fill Explosive	Hand Packed	Hopper Fed	Batch filled	One By One	Outsourced Complete Shaped Charge		
Pack Shaped Charge for Transport	By Hand	By Machine	Automated	Outsourced	Outsourced Complete Shaped Charge		
Receive Drone	Outsourced	Made In House					
Receive Radar	Outsourced	Made In House					
Receive UGV	Outsourced	Made In House					
Receive Plow	Outsourced	Made In House					
Manufacture Drone Mounting Systems	Welded	Steel	Aluminium	Outsourced Complete Mounting System	3D Print	Laser Cut	Tubular Frames
Manufacture UGV Plow Mounting System	Welded	Steel	Aluminium	Outsourced Plow System	3D Print	Laser Cut	Tubular Frames
Assemble UGV Plow System	By Hand	By Machine	Automated	Outsourced Complete Drone System			
Assemble Drone System	By Hand	By Machine	Automated	Outsourced Complete Drone System			
Pack Drone System / UGV For Transport	By Hand	By Machine	Automated	Outsourced Complete Drone System / UGV			

Figure 22 - Manufacturing FMA

		Relative Importance Equal	Relative Importance Weighted	Benchmark Complete Self Made	Alternative Buy In Case & Cone - Self Fill	Alternative Buy Complete Unit Shaped Charge
WHATs - Customer Requirements	How much:- From QFD 1					
Manufacturing Requirements						
Manufacturing Costs						
Labour		5	5	0	1	2
Equipment capital cost		5	5	0	1	2
Service / Operating Cost		5	5	0	1	2
Set up cost		5	5	0	1	2
Material Cost - Metal Bits		5	5	0	1	2
Material Cost - Energetic Bits		5	5	0	1	2
Material Cost - other		5	5	0	1	2
Maintenance Cost		5	5	0	1	2
Manufacturing Capacity						
Target production rate XX per month		5	5	0	0	0
Reliable Manufacture						
Repeatable performance		5	5	0	0	0
Effective Maintenance		5	5	0	1	2
Low system outage		5	5	0	0	0
Quality						
Defect Free		5	5	0	0	0
Effective test and inspection		5	5	0	0	0
Safety						
Explosive		5	5	0	0	0
Non-Explosive		5	5	0	0	0
		Un Weighted		0	45	90

Figure 23 - Manufacturing Systems Pugh

Design feature	Importance	3D Print Case	3D Print Cone	Explosive Made In House	Explosive Mixed In Mixing Bowl	Case / Cone Cleaned By Chemical Wash	Shaped Charge Assembled By Hand	Explosive Hand Packed	Shaped Charge Packed For Transport By Hand	Drone Bought In	Radar Bought In	UGV Bought In	Plow Bought In	Drone Mounting Systems 3D Printed	UGV Plow Mounting System 3D Printed	Assemble UGV Plow Mounting System By Hand	Drone System Assembled By Hand	Drone System / UGV Packed For Transport By Hand
Functionality																		
Manufacture Case	35	9	1			3	3	1	1					3				
Manufacture Cone	35	1	9			3	3	1	1					1				
Receive Explosive	26			9				3	1									
Mix Explosive	44			9	9			3	1									
Clean Case / Cone	24.5	3	3			9	3	3	1									
Assemble Shaped Charge	24.5	3	3			3	9	3	3					3				
Fill Explosive	39.5	1	1	3	3	3	1	9	1									
Pack Shaped Charge for Transport	26	3	3	1		1	3	3	9									
Receive Drone	23									9							3	
Receive Radar	23										9						3	
Receive UGV	23											9			1	3		
Receive Plow	23												9		3	3		
Manufacture Drone Mounting Systems	38	3	3				1	1	1	3	3			9			3	1
Manufacture UGV Plow Mounting System	39											3	3		9	3		1
Assemble UGV Plow System	29											3	3		3	9		3
Assemble Drone System	20.5	3	3				1	1	1	3	3			3			9	3
Pack Drone System / UGV For Transport	26	1	1			1	1	1	1	3	3	3	3	1	1	1		9
		816	816	775	515	675	706	945	596	461	461	489	489	643	556	542	437	460

Figure 24 - Manufacturing QFD 2

Appendix B

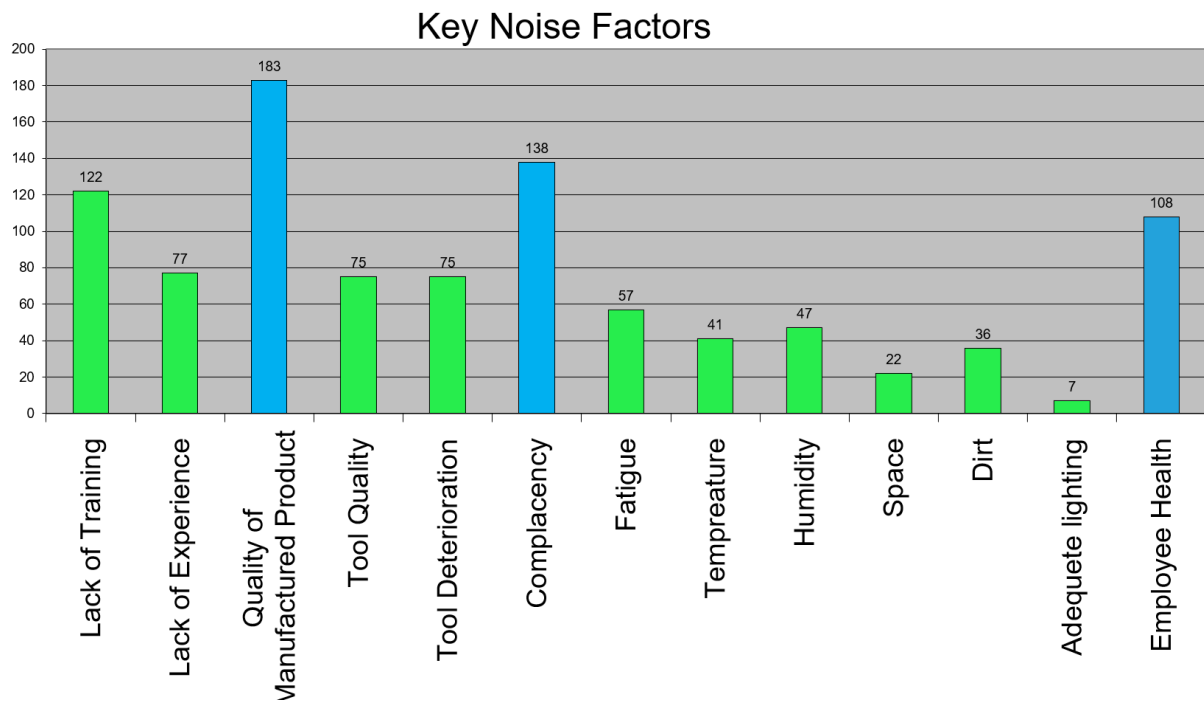


Figure 25 - Key Noise Factors of Safety Manufacturing

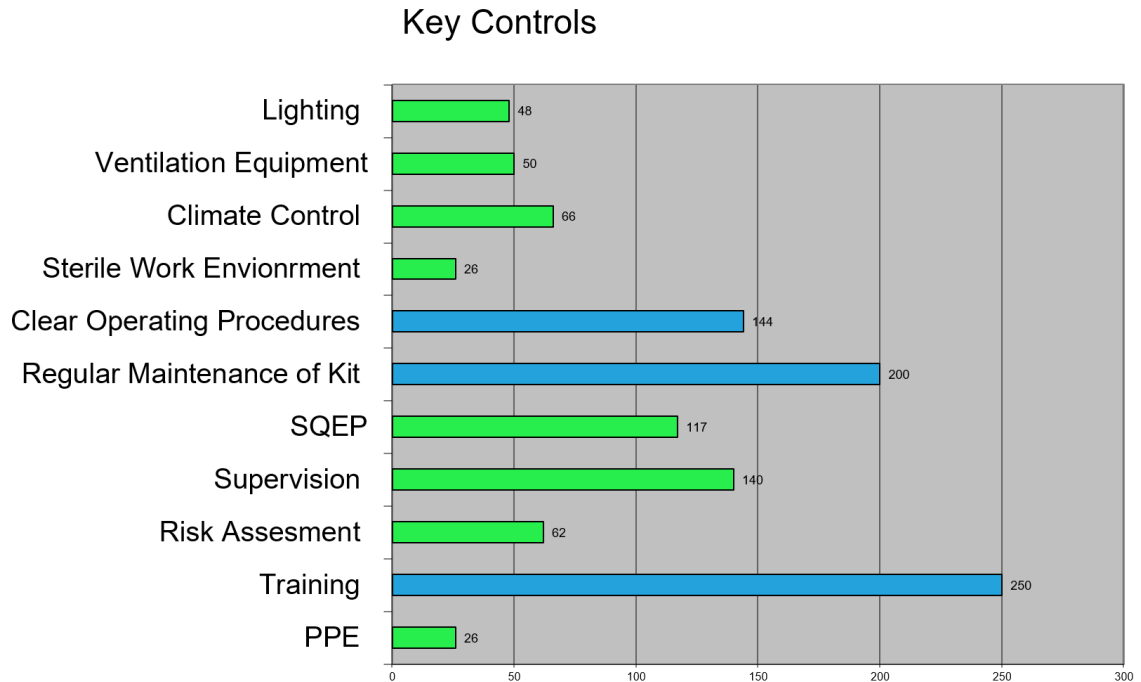


Figure 26 - Key Control Factors of Safety Manufacturing