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Systems Thinking Design Report

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Computing
Ordnance, Munitions and Explosives

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Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- no animals were harmed in the writing of this essay.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
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Abstract

The design team, working to a provided brief, used systems engineering methodology to design, analyse and manufacture a working system within a tight timeframe, working closely with key project stakeholders. As trials and evaluation representative for the group, the author identified opportunities during the design process to develop the appropriate tests, working alongside the research and development department to establish benchmark performance standards.

Keywords:

Systems engineering, test and evaluation, mine clearance, quality function deployment, drone

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List of Abbreviations

APBF	Anti-Personnel Bounding Fragmentation
AT	Anti-Tank
COTS	Commercial Off-The-Shelf
FMA	Function Means Analysis
GPR	Ground Penetrating Radar
HE	High Explosive
QFD	Quality Function Deployment
T&E	Test and Evaluation
UGV	Unmanned Ground Vehicle

1 Introduction

As part of a small team, the author used systems engineering methodology to generate a design which would solve a complex and novel problem.

During the design process, the team were divided into roles to ensure that each aspect of the design process was addressed. The author accepted the role of Test and Evaluation (T&E) lead for the project, a role which made the author responsible for [1]:

- Creation of tests for both the system as a whole and individual subsystems.
- Performing tests at each stage of the design process.
- Delivering results to schedule to ensure the project could move forwards at pace.
- Identification of faults and communication to the appropriate department.

As well as these responsibilities, the author was involved in the full design process as well as the presentation of the design to key stakeholders.

2 Scenario

The customer required a system which could identify, mark and neutralise land mines in a desert environment. The system was to be light weight, transportable by land and rapidly clear the contaminated area. There was to be an emphasis on speed, as the system was in demand for a time-sensitive operation.

The full design brief for the project can be found within Appendix A.

2.1 Explosive threats

A clear understanding of the explosive threats was key to the production of a design. It was stated by the customer that the contaminated area contained both the Russian OZM-72, and the American M15 mines. The author performed research into these mines on the online METIS program [2] and learned the following information:

2.1.1 OZM-72

The OZM-72 is a large, metal cased Anti-Personnel Bounding Fragmentation (APBF) mine which may be triggered through pressure, tripwire, command wire, or seismic fusing [1]. When triggered, the OZM-72 has a lethal radius of roughly 25 m.

2.1.2 M15 HE

The M15 High Explosive (HE) mine is a large, metal cased Anti-Tank (AT) mine which may be triggered by pressure exceeding 159 kg, or by a tilt rod [2]. The M15 contains roughly 10 kg of TNT [2] and, when triggered, is capable of completely destroying light vehicles.

Both the OZM-72 and the M15 may sympathetically detonate when subjected to a high explosive shockwave.

3 Concept generation

Following the Quality Function Deployment (QFD) model [5], The team completed the following steps to generate a design concept:

1. Generation of a stakeholder map to identify key stakeholders
2. Engagement with stakeholders to set requirements
3. Analysis of requirements to identify functions
4. Creation of a function flow diagram
5. Exploration of solutions for each function
6. Selection of function means

3.1 Requirements

3.1.1 Stakeholder identification

A stakeholder map was generated to identify key stakeholders for the system. These stakeholders were identified as:

- The user: this refers to the personnel operating the system.
- The logistics team: this refers to the organisation responsible for packaging and transporting the system.

- The customer: this refers to the organisation managing the in-service life of the system
- The legislative body: this refers to the various organisations legislating the design and use of the system.

3.1.2 Requirements setting

Engagement with the above stakeholders generated the following requirements:

Originator	Requirement #	Requirement
User	1	The system shall be simple to use
	2	The system shall be safe to use
	3	The system should be easy to maintain
Customer	4	The system shall identify M15 and OZM-72 mines
	5	The system shall communicate the location of M15 and OZM-72 mines
	6	The system shall clear M15 and OZM-72 mines
	7	The system shall have a high mechanical reliability
	8	The system shall operate in a desert environment
	9	The system shall withstand bullet and fragment attack
Logistics team	10	The system should be of manageable size and weight for transport
Legislative body	11	The environmental impact of the manufacturing process must be kept to a minimum.
	12	The environmental impact of the disposal of the system must be kept to a minimum
	13	The design of the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE
	14	The manufacturing process must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE
	15	The transportation and storage of the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE
	16	The system must be disposed of in accordance with the relevant standards

Table 1 - System requirements

3.1.3 Requirements ranking

Once the requirements had been set, the pairwise comparison tool was used to identify the key requirements and enable the design team to prioritise correctly. The full pairwise comparison, contained within Appendix B, was performed according to the approved method [6] by the entire design team and provided the following rankings:

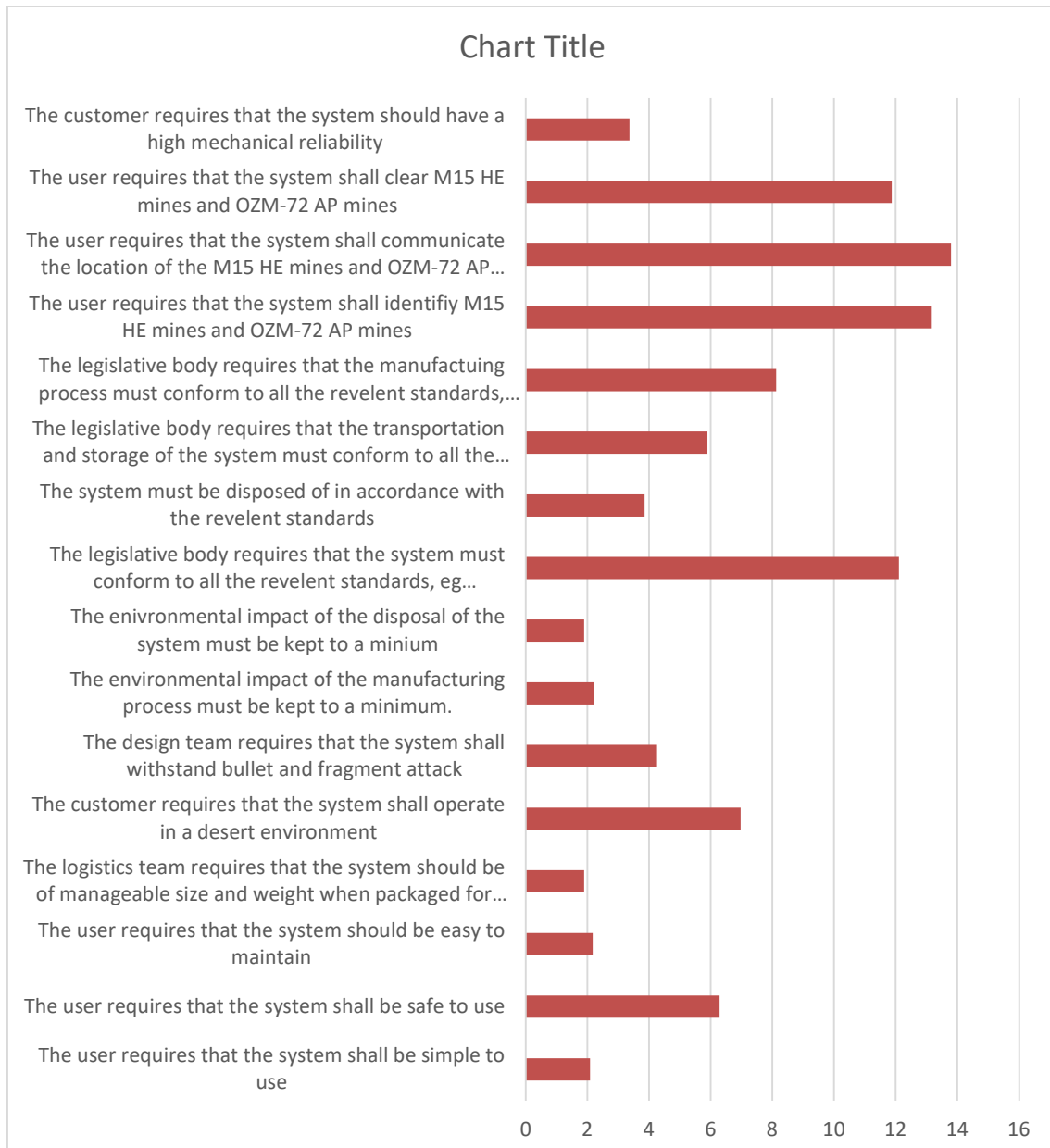


Figure 1 - Pairwise comparison results

Figure 1 shows that the three most important requirements were those of the user that the system shall identify, communicate the location of, and then clear the threat articles. This reflects the design teams awareness that the design was required urgently, and that trade-offs could be made in the areas of mechanical reliability and user-friendliness to allow for a robust and effective design which would perform the required task.

The identification and prioritisation of requirements assisted the T&E team through identifying areas of the design in which final acceptance testing would likely be most relevant. For example, the requirement for identification and disposal of explosive articles, combined with the detailed knowledge gained of these articles, gave the T&E team an indication of the nature of tests which would be required to verify this specific capability.

3.2 Functions

The requirements contained within Table 1 include both functional (*the system shall clear...*) and non-functional (*the system must conform...*) requirements. The functional requirements were used to create the following list of functions:

Function #	Function
1	Be deployed
2	Survive desert environment
3	Resist kinetic attack
4	Interface with energy source
5	Receive command
6	Move
7	Detect mine
8	Communicate location of mine
9	Clear mine
10	Be recoverable

11	Be disposable
----	---------------

Table 2 - Design functions

With the functions established, QFD 1 was performed to establish the relative importance of these functions, which would serve to later inform upon component criticality. The full QFD 1 process, shown in Appendix C, was completed by the entire team and produced the following results:

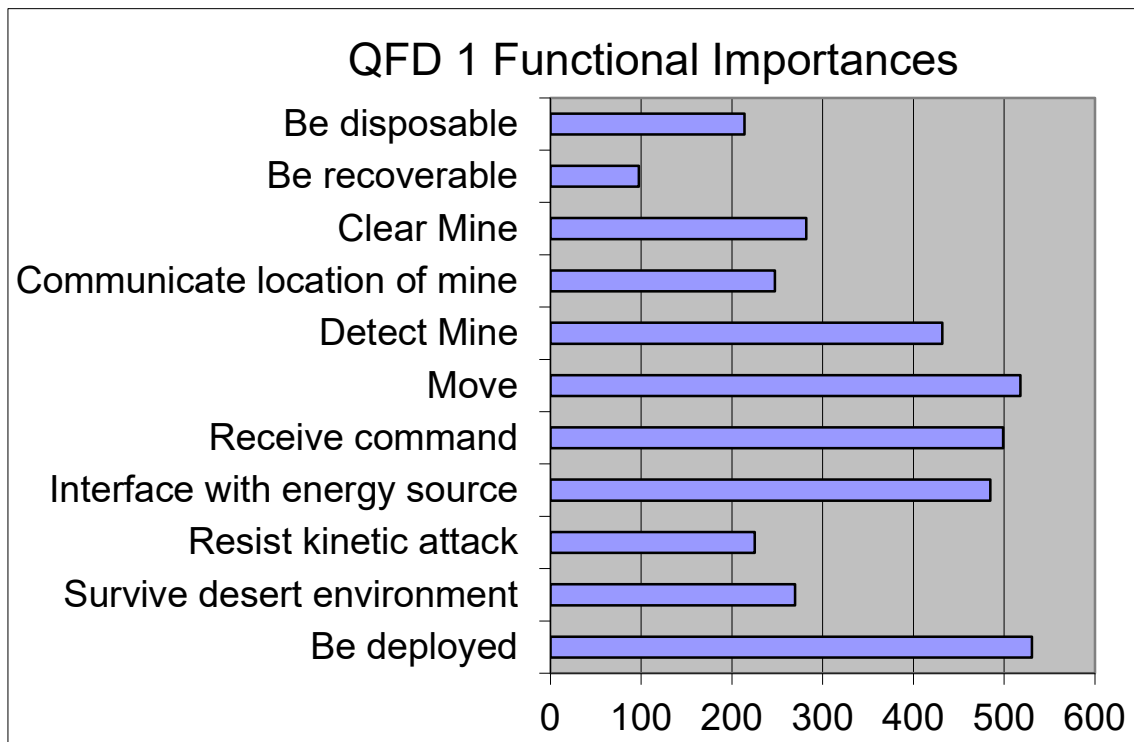


Figure 2 - Functional importances

Figure 2 shows a clear gradient from a high importance attached to functions at the early stages of operation (be deployed, move) to a lower importance in the later stages, with importance dropping sharply after the mine has been detected. This illustrates the awareness of the design team of the compromises required in a time-limited design process. A detected mine is far less of a threat than an unidentified mine and, as long as a mine has been identified and mapped, other solutions may exist to either neutralise or avoid the mine.

The identification of functions, as well as their individual importances, was highly relevant to the T&E team. While it was too early in the process to design specific

tests, the functions listed allowed the T&E department to identify the general nature of testing to be carried out and to begin scoping requirements for testing equipment and facilities (for example, explosive ranges) which were likely to be needed later in the project.

4 Concept

4.1 Concept derivation

Concepts were derived through the production of a Function Means Analysis (FMA). An FMA involves the creation of various solutions for each function, which were arranged in a table. Solutions according to a theme (for example, low cost or high reliability) are then identified for each function, creating 'pathways' which generate a full concept on that particular theme [7].

Appendix D contains several illustrations of FMAs undertaken by the team, as well as the FMA which produced the final design.

4.2 Concept selection

The FMAs undertaken by the team produced several concepts. In order to select a final concept, the team performed a Pugh analysis. The baseline concept used for this was a clearance operator using a metal detector to identify mines.

Being compared with this concept were a drone-based system (a high tech concept), an Unmanned Ground Vehicle (UGV) (a high reliability concept), and a plough affixed to a 4x4 (a low cost concept).

	Relative Importance Equal	Relative Importance Weighted	Man with metal detector	Drone	UGV	Plough on 4x4
WHATs - Customer Requirements						
The customer requires that the system shall operate in a desert environment	2		0	1	1	1
The design team requires that the system shall withstand bullet and fragment attack	6		0	0	2	1
The environmental impact of the manufacturing process must be kept to a minimum.	2		0	0	-1	-1
The environmental impact of the disposal of the system must be kept to a minimum	2		0	0	-2	-1
The legislative body requires that the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	7		0	0	0	0
The system must be disposed of in accordance with the relevant standards	4		0	0	0	0
The legislative body requires that the transportation and storage of the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	2		0	0	0	0
The legislative body requires that the manufacturing process must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	2		0	0	0	0
The user requires that the system shall identify M15 HE mines and OZM-72 AP mines	12		0	2	-1	-2
The user requires that the system shall communicate the location of the M15 HE mines and OZM-72 AP mines	4		0	1	-1	0
The user requires that the system shall clear M15 HE mines and OZM-72 AP mines	6		0	2	2	-1
The customer requires that the system should have a high mechanical reliability	8		0	1	1	2
Ranking			0	50.0808	12.66134462	-9.544463948
			0	0	0	0
	100		0	50.0808	12.66134462	-9.544463948

Figure 3 - Pugh matrix

The Pugh matrix was undertaken by the whole group. The drone concept scored relatively highly across the board, losing points only in withstanding bullet and fragment attack. It was judged that the drone, as a stable platform for sophisticated mine detection systems, would identify M15 and OZM-72 mines more effectively than the other concepts.

The UGV scored well on withstanding bullet and fragment attack as such systems can have a much higher weight than drones and therefore incorporate an amount

of armour plating into the design. However, it was judged that a UGV would be less effective at identifying and clearing mines than a human operator due to a lowered operator situational awareness from remote cameras [8].

A 4x4 mounted plough scored poorly on identification and detection of mines. It was decided by the team that the accidental initiation of a mine and consequent total destruction of the system, while an effective way to detect a mine and communicate its location, was neither cost effective nor safe.

The Pugh matrix helped the team to identify the Drone based system as the concept most in line with customer requirements, and this was the concept that the team chose to take forwards.

4.3 Final concept

The final concept derived was that of a drone of quadcopter type, controlled by an operator through a fibre optic connection. This drone would have a modular underslung load system to enable it to carry either a metal detection subsystem, a Ground Penetrating Radar (GPR) subsystem, or a release mechanism which would drop a thermite device.

The system would use the GPR subsystem to locate buried objects within the contaminated area, with detected threats being mapped digitally. A confirmation sweep with the metal detection subsystem would differentiate erroneous contacts (such as buried rocks) from threat articles. Those contacts confirmed as metallic would then be burned using a thermite charge.

Due to the tight timeframe for the project, the design team would procure most components as Commercial Off-The-Shelf (COTS) products, rather than spending time developing these components from the ground up.

With the final concept established, the T&E team began research to establish testing regimes for the metal detection, GPR and thermite subsystems.

5 Concept evaluation

With a final concept derived, the design team examined the key features of the system to identify critical components and the sources and impact of noise.

5.1 Component criticality

The design team performed QFD 2 on the chosen design. QFD 2 scores design features against functionality [5], allowing a designer to visualise which design features are critical to both the performance of a critical task, and the operation of the system as a whole.

The full QFD 2 is contained within Appendix E, with the results summarised in Figure 4 below. The QFD 2 table shows a strong diagonal as features are identified as critical to functionality.

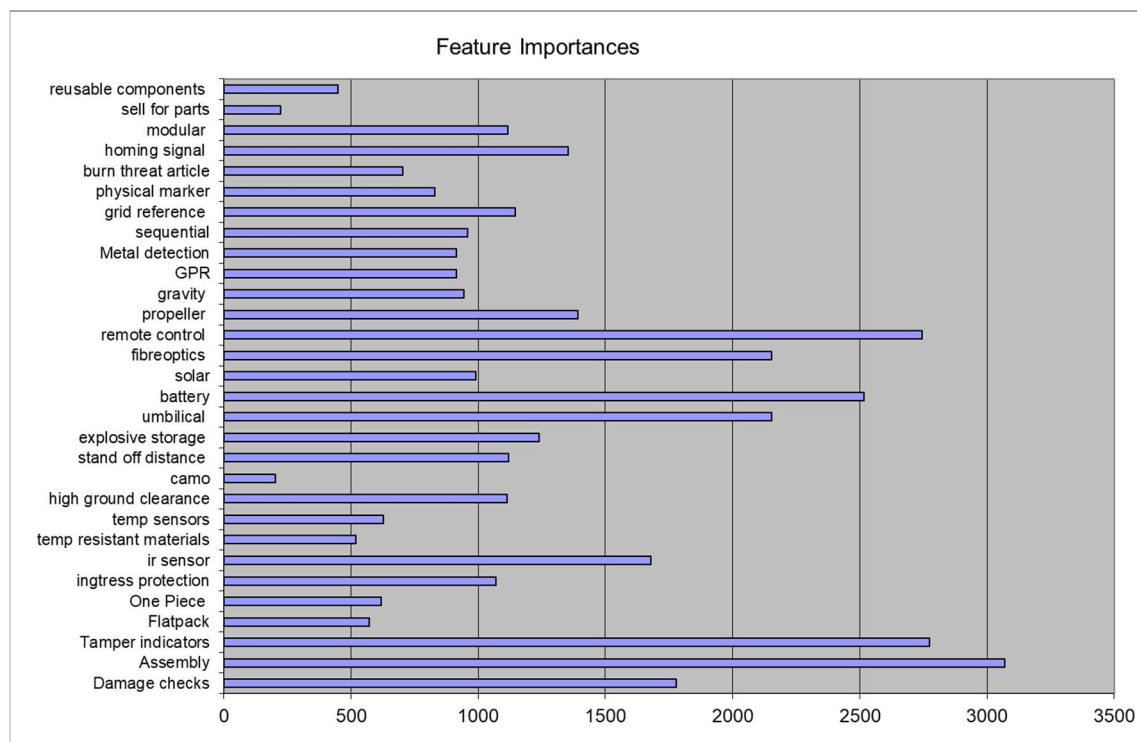


Figure 4 - QFD 2 results

Figure 4 shows that features with high importance included the ability to assemble and control the system; this is likely due to the fact that these features enable other features (such as flight and metal detection) to be fully utilised. A failure in

assembly (a broken connector) or a failure of the remote control system would lead to a critical failure of the entire system.

Features with low criticality included camouflage paint for the system – a solution to the requirement that it be resistant to bullet and fragment attack – and disposal solutions such as reusable or resaleable parts. In the latter two cases, this is due to these features having no impact on the ability of the drone to carry out its key functionality of detecting, marking and neutralising mines.

The identification of critical components further informed the T&E department, which established a robust acceptance testing programme for the identified design features including the stress testing of connectors, fibre optic connectivity testing, and battery performance testing. In the case of COTS items, the T&E team began engaging with manufacturers in order to confirm that those manufacturers' in-house T&E processes were robust and to standard.

5.2 Noise

The impact of noise was examined on those subsystems which the QFD 2 process had identified as critical to the functionality of the design. These included the GPR subsystem, the flight subsystem and the remote control subsystem.

5.2.1 P diagrams

To understand the threat to these critical components from noise factors, the design team undertook a number of P-diagrams to explore the sources and impact of 'noise' on critical subsystems. P-diagrams are systems engineering tools which consider the following noise factors [9]:

- External: sources of variance from outside the subsystem.
- Unit to unit: variation between multiples of the same unit.
- Deterioration: variation over time due to the deterioration of the system.

An example P-Diagram is shown below in Figure 5, which examines the impact of noise on the GPR subsystem.

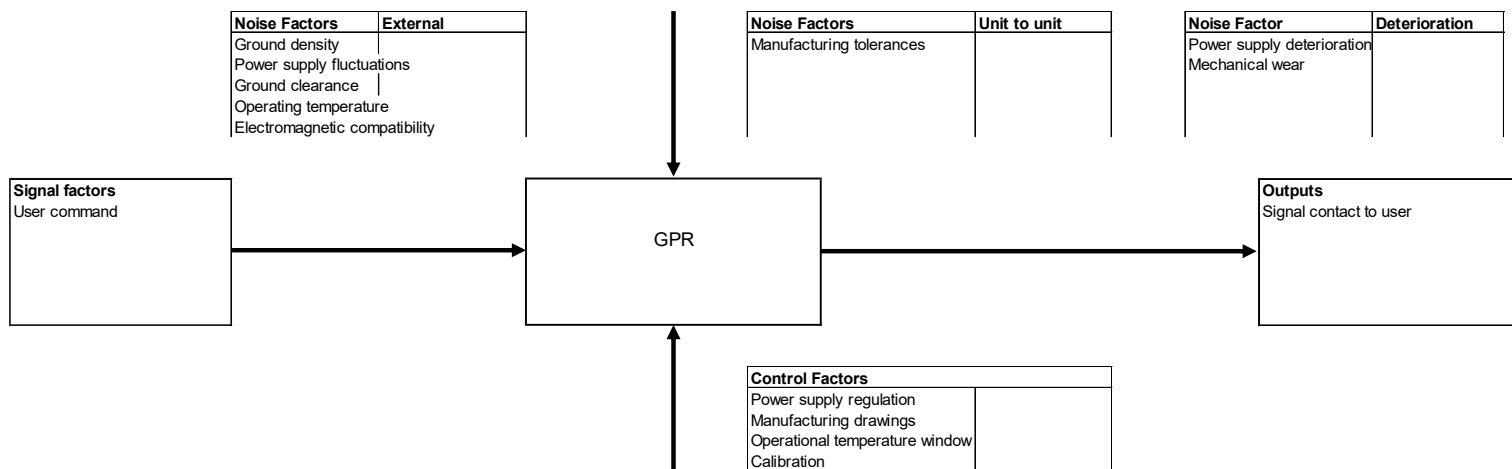


Figure 5 - P diagram (GPR)

Analysis of the sources and impact of noise on these critical subsystems enabled the design team to identify areas of the manufacturing process which required particular control factors in order to reduce the impact of external noise, the degree of unit-to-unit variation, and the deterioration of subsystems.

5.2.2 What why tables

Once control factors were identified for each subsystem, the relative importance of these factors was established using 'What Why' tables, as in Figure 6 below:

	Weighting of design control parameter	Unit to Unit Variation			Deterioration			External					Total
		Mfg			Raw Mat'l			Environment					
Design control parameters		Manufacturing tolerances			Power supply deterioration	Mechanical wear		Ground density	Power supply fluctuation	Ground clearance	Operating temperature	Electromagnetic compatibility	
Power supply regulation					3				9			3	15
Manufacturing drawings		9											9
Operational temperature window		3			9				3		9		24
Calibration					3			9		3			15

Figure 6 - What Why table (GPR subsystem)

Figure 6 shows the impact of each control factor on each source of noise, with 9 being a high impact, 3 being a moderate impact, 1 being a low impact and a blank space indicating no impact. The total scores for each control factor is shown on the far right, and in this case indicates that the determination of an operational temperature window is highly important in reducing the impact of noise. Conversely the production of detailed manufacturing drawings, while critical for reducing unit to unit variation, does little to reduce the impact of external noise or deterioration.

The lessons learned from the What Why tables enabled the design team to prioritise control factors by their effectiveness, as well as to introduce control measures to address noise where it could not be designed or manufactured out of the system. This in turn informed the T&E team on acceptable variation during the acceptance testing of COTS components, final acceptance testing of completed systems, and scheduled maintenance of the system when in service.

6 Manufacturing

With a concept selected, the critical subsystems and components identified, and the impact of noise on the system understood, the design team moved on to the manufacturing phase of the project.

6.1 Manufacturing requirements

The design team engaged with key manufacturing stakeholders to establish a set of requirements for the manufacturing process. These requirements are contained within Table 3:

Originator	Requirement #	Requirement
Accounting team	1	The cost of skilled labour should be as low as possible
	2	The equipment capital cost should be controlled to a minimum
	3	The operating cost should be controlled to a minimum
	4	The process set up cost should be controlled to a minimum
	5	The cost of raw materials should be as low as possible
	6	The cost of maintenance should be controlled to a minimum
Customer	7	The production rate shall not be lower than 20 per month
Plant management	8	The manufacturing process shall be reliable and repeatable
	9	The manufacturing process should have a low outage rate
	10	The product manufactured shall be defect free
	11	Effective test and inspection of products shall be carried out
Safety team	12	Those processes involving energetics shall be carried out safely
	13	Those processes not involving energetics shall be carried out safely

Table 3 - Manufacturing requirements

6.2 Manufacturing QFD 1

The design team worked alongside key manufacturing stakeholders, including suppliers and plant managers, to create process maps for the manufacture of each subsystem. An example of these, the process map for the drone flight subsystem, is shown below:

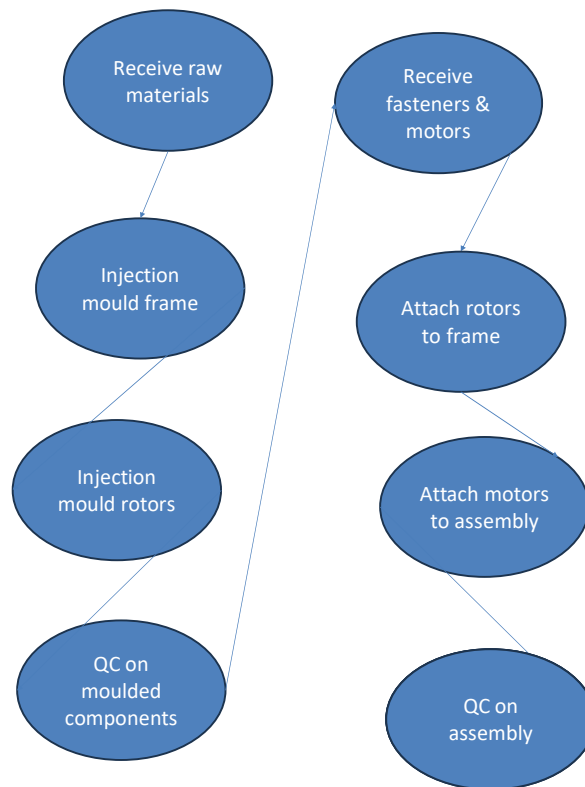


Figure 7 - Drone flight subsystem manufacture process map

The process maps created enabled the design team to perform QFD 1 of the manufacturing process for each subsystem. The results of this are shown below:

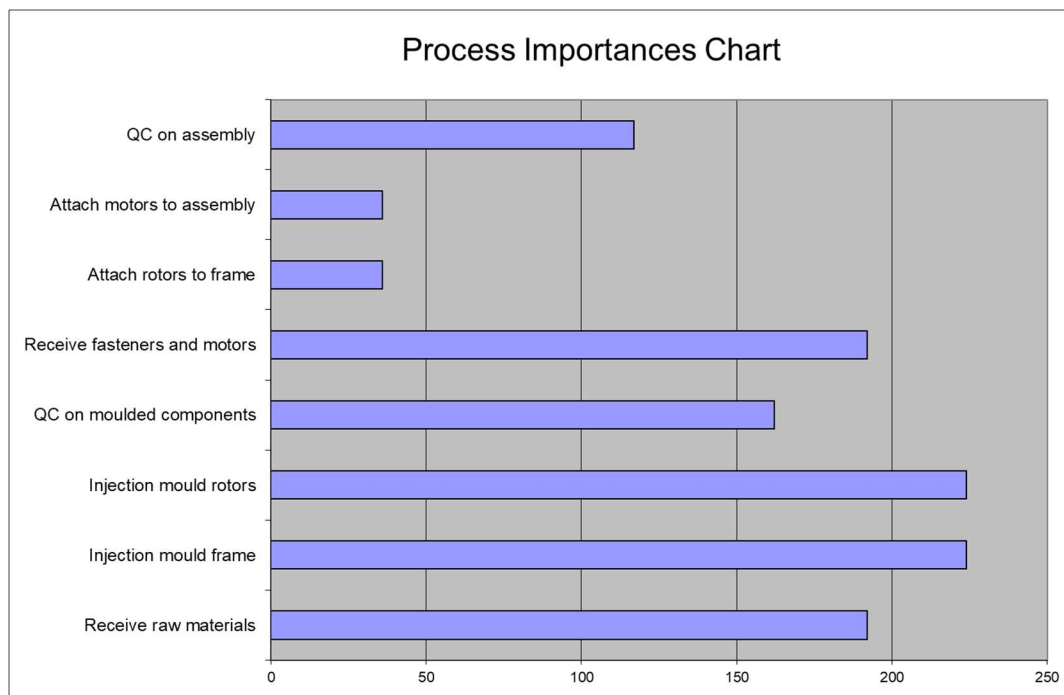


Figure 8 - Process importances (drone flight subsystem)

Figure 8 shows that the processes which were assessed as most important were the injection moulding of the plastic components and the shipping of the raw materials. This allowed the design team to prioritise resources – both human and financial – to those areas ensuring that the manufacturing process for this subsystem ran to requirements.

During this phase of the design the T&E team worked closely alongside the thermite research team to identify the tolerances for the thermite mixes being developed.

6.3 Manufacturing noise

As with the design subsystems, the sources and effects of noise on the manufacturing process was examined by the design team through the use of P diagrams.

Figure 9 shows the P diagram relating to the injection moulding processes:

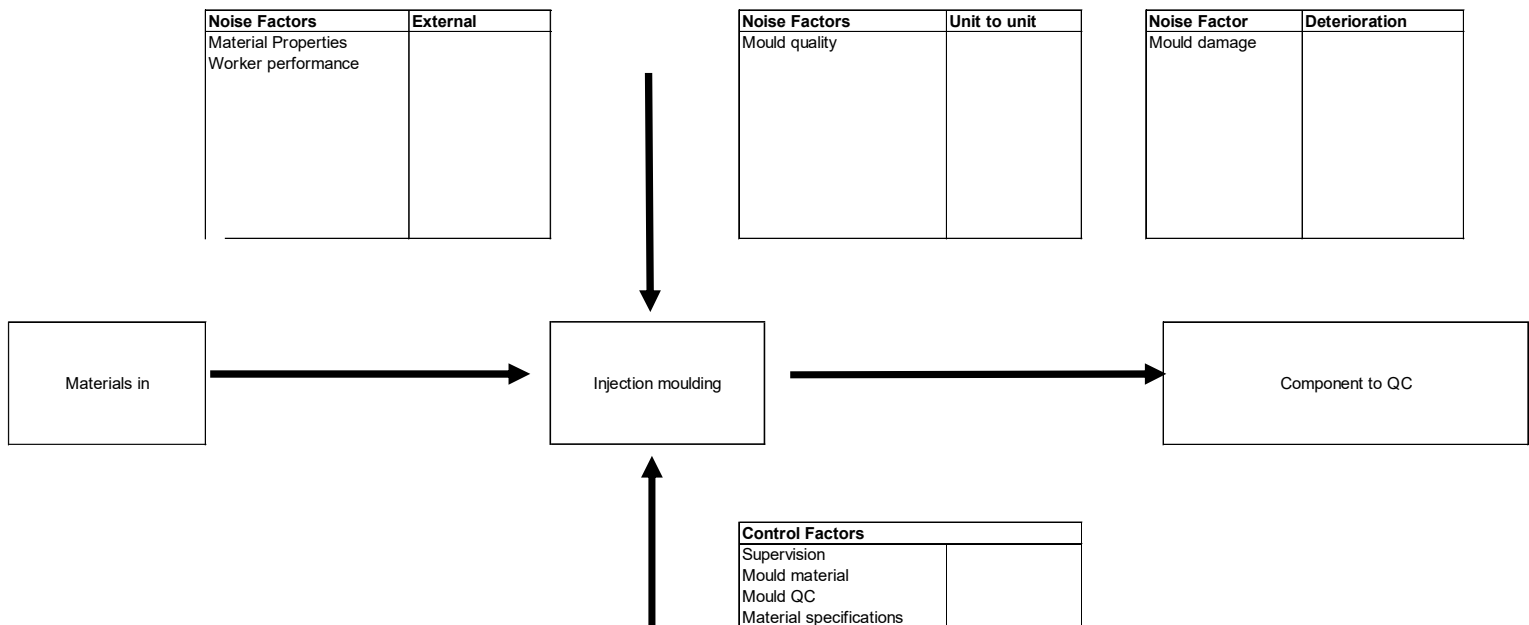


Figure 9 - P diagram for injection moulding

As with system noise, the noise factors and control factors were then translated into a What Why table to examine the impact of control factors on sources of noise. The results of this What Why analysis, shown in Figure 10, indicate that the quality control of the moulds used to manufacture the plastic components is a critical step in reducing noise for this process.

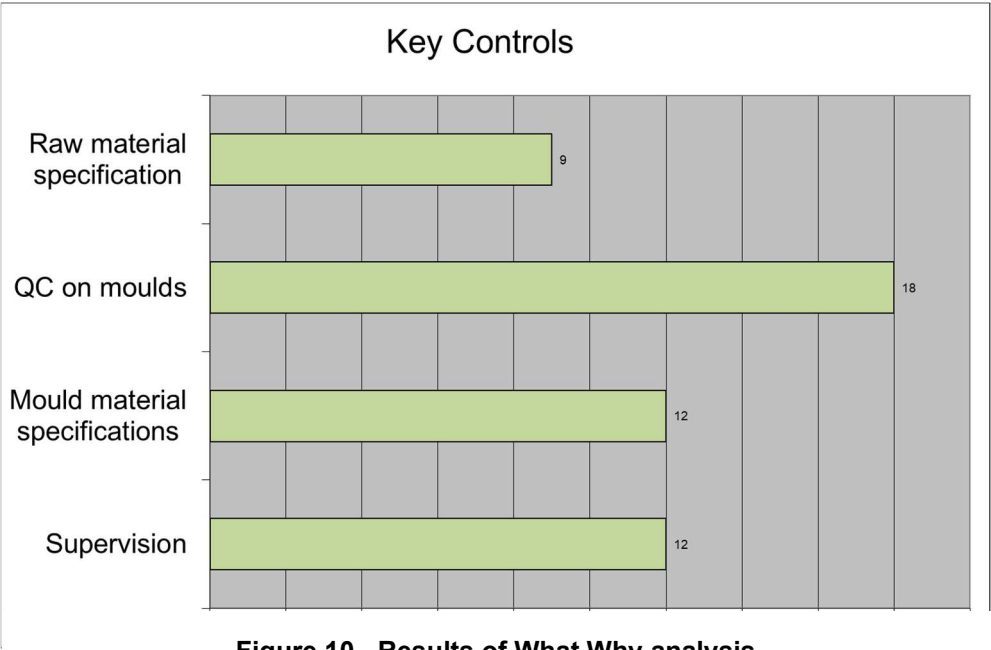


Figure 10 - Results of What Why analysis

7 Add some kind of conclusion

The design team were provided with a complex problem to solve within a short timeframe. Using systems engineering tools and working closely with key stakeholders, the design team took a project from an initial set of requirements through to a suitable concept, and further engaged with manufacturing stakeholders to develop a robust manufacturing process to deliver a quality product on time and to specifications.

As T&E representative, the author took opportunities at every stage of the design to identify information pertinent to the T&E department, ensuring that benchmark performance standards were established and the appropriate performance tests developed to ensure that the product delivered was performing to customer requirements.

2644 words

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Appendix A - Full design brief

The Design Brief

- The design scenario is that we have a column of supplies (Medical) traversing desert terrain. The approved route will come across a mined area.
- The mined area is within a steep walled pass. Go-around is difficult, if not impossible. A persistent ground to air MANPAD threat makes helicopter use too risky. As we need to open up the route for civilian medical transport for subsequent convoys the road route is much preferred.
- Time on the operation is critical. The emphasis is on a rapid move in, clear the objects and move on.
- The indigenous population do not have easy access to helicopter transport. The mission is to get the convoy. (Nothing heavier than a Land Rover or ubiquitous Toyota trucks) carrying their delicate cargo through the mined area and leave the area clear for subsequent transport.
- I will present several mine clearing options as a functional guide. The grand Panjandrum, the progression from Conger to Viper to Python, flails, and rollers.
- Unfortunately, the use of Python is banned because there is a perceived vulnerability against bullet / fragment attack and also that misfires or capture would afford the opportunity of furnishing any hostiles with explosive resources.
- There is also an issue with transporting heavy vehicles to the location. There's a driveshaft/gearbox issue with the low loaders required to bring heavy vehicles forward. Someone forgot to fit the gaiters that keep the dust out. Most of the fleet is awaiting spare parts or have been reserved for combat missions rather than humanitarian exercises.
- The teams are required to design a portable (Land Rover or Hi-Lux) mine detection, clearing and marking system to ensure safe passage for this and future convoys.
- The customer needs to know design, functionality, subcomponent design, critical feature identification, critical manufacturing process controls, (Or what is it? What does it do? Can you make it? What are the tricky bits? How are you going to make sure it works?)
- The threat articles will be described later in the brief.

Appendix B – Pairwise comparison

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 user requires that the system shall be simple to use	The user requires that the system shall be safe to use	The user requires that the system should be easy to maintain	The logistics team requires that the system should be of manageable size and weight when packaged for transport	The customer requires that the system shall operate in a desert environment	The design team requires that the system shall withstand bullet and fragment attack	The environmental impact of the manufacturing process must be kept to a minimum	The environmental impact of the disposal of the system must be kept to a minimum	The legislative body requires that the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	The system must be disposed of in accordance with the relevant standards	The legislative body requires that the transportation and storage of the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	The legislative body requires that the manufacturing process must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	The user requires that the system shall identify M15 HE mines and OZM-72 AP mines	The user requires that the system shall communicate the location of the M15 HE mines and OZM-72 AP mines	The user requires that the system shall clear M15 HE mines and OZM-72 AP mines	The customer requires that the system should have a high mechanical reliability	Row Product	nth root of row product	Total Normalised
The user requires that the system shall be simple to use	1	0.11	5	2	0.2	0.2	0.5	0.5	0.11	0.5	0.5	0.2	0.11	0.11	0.11	0.5	0	0	2.1
The user requires that the system shall be safe to use	9	1	5	5	2	0.5	2	2	1	2	2	1	0.2	0.2	0.2	5	144	1	6.3
The user requires that the system should be easy to maintain	0.2	0.2	1	2	0.5	0.2	2	5	0.2	0.5	0.2	0.2	0.11	0.11	0.11	0.2	8.5184E-08	0	2.2
The logistics team requires that the system should be of manageable size and weight when packaged for transport	0.5	0.2	0.5	1	0.2	0.11	2	1	0.2	0.5	0.5	0.2	0.11	0.11	0.11	0.2	5.8564E-09	0	1.9
The customer requires that the system shall operate in a desert environment	5	0.5	2	5	1	2	5	9	1	5	1	1	0.5	0.2	0.5	2	1125	1	7
The design team requires that the system shall withstand bullet and fragment attack	5	2	5	9	0.5	1	5	5	0.2	2	0.2	0.2	0.11	0.11	0.11	0.5	0.059895	1	4.3
The environmental impact of the manufacturing process must be kept to a minimum	2	0.5	0.5	0.5	0.2	0.2	1	2	0.2	0.5	0.5	0.2	0.11	0.11	0.11	0.5	1.331E-07	0	2.2
The environmental impact of the disposal of the system must be kept to a minimum	2	0.5	0.2	1	0.11	0.2	0.5	1	0.2	0.5	0.5	0.2	0.11	0.11	0.11	0.2	5.8564E-09	0	1.9
The legislative body requires that the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	9	1	5	5	1	5	5	5	1	2	2	1	5	5	5	5	70312500	2	12
The system must be disposed of in accordance with the relevant standards	2	0.5	2	2	0.2	0.5	2	2	0.5	1	0.2	0.2	0.5	0.5	0.5	2	0.008	1	3.9
The legislative body requires that the transportation and storage of the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	2	0.5	5	2	1	5	2	2	0.5	5	1	2	0.2	0.2	0.2	5	40	1	5.9
The legislative body requires that the manufacturing process must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	5	1	5	5	1	5	5	5	1	5	0.5	1	0.5	0.5	0.5	5	24414.0625	2	8.1
The user requires that the system shall identify M15 HE mines and OZM-72 AP mines	9	5	9	9	2	9	9	9	0.2	2	5	2	1	1	2	9	382637520	3	13
The user requires that the system shall communicate the location of the M15 HE mines and OZM-72 AP mines	9	5	9	9	5	9	9	9	0.2	2	5	2	1	1	2	9	956593800	3	14
The user requires that the system shall clear M15 HE mines and OZM-72 AP mines	9	5	9	9	2	9	9	9	0.2	2	5	2	0.5	0.5	1	9	47829690	2	12
The customer requires that the system should have a high mechanical reliability	2	0.2	5	5	0.5	2	2	5	0.2	0.5	0.2	0.2	0.11	0.11	0.11	1	0.0005324	1	3.4

Appendix C – QFD 1

How	Importance	Be deployed	Survive desert environment	Resist kinetic attack	Interface with energy source	Receive command	Move	Detect Mine	Communicate location of mine	Clear Mine	Be recoverable	Be disposable
Requirements												
The user requires that the system shall be simple to use	2.1	3	1		1	9	3	1	3	3		
The user requires that the system shall be safe to use	6.3	9		3	9	9	3	1	1	9	3	1
The user requires that the system should be easy to maintain	2.2	1	9	3	3	1	9			3		
The logistics team requires that the system should be of manageable size and weight when packaged for transport	1.9	9	3	1							1	3
The customer requires that the system shall operate in a desert environment	7	3	9		1	3	9	3	3	1	1	
The design team requires that the system shall withstand bullet and fragment attack	4.3	1		9	3	1	3	1	1	9	3	1
The environmental impact of the manufacturing process must be kept to a minimum.	2.2		3	3	9			1	1			3
The environmental impact of the disposal of the system must be kept to a minimum	1.9	3								1	3	9
The legislative body requires that the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	12	1	1	1	1	3	1	1	3	3	1	9
The system must be disposed of in accordance with the relevant standards	3.9	1								1	3	9
The legislative body requires that the transportation and storage of the system must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	5.9	3	1	1			1				3	1
The legislative body requires that the manufacturing process must conform to all the relevant standards, eg International Mine Action Standards, COSHH, REACH, ADRM, STANAGs, Def Stans and HSE	8.1	3	1	1	1			3	1	1		3
The user requires that the system shall identify M15 HE mines and OZM-72 AP mines	13	9	3	3	9	9	9	9				
The user requires that the system shall communicate the location of the M15 HE mines and OZM-72 AP mines	14	9	3	3	9	9	9	9	9			
The user requires that the system shall clear M15 HE mines and OZM-72 AP mines	12	9	3	3	9	9	9	9	3	9		
The customer requires that the system should have a high mechanical reliability	3.4	3	9	3	3	3	9	3	1	3	3	

Appendix D – FMA

Function	Means														
Be deployed	Damage checks	Assembly	Preuse checks	Flatpack	Inflate	Foldable	Air droppable	One piece							
Survive desert environment	Reinforced frame	Ingress protection	Filtration	IR sensors	Sun shielding	temperature resistant materials	Heat reflective Coating	Sun cream	Phase change materials	Air vents	Air/ Liquid Cooling	Insulation	Expansion tollerant materials	Temperature Sensors	High ground clearance
Resist kinetic attack	Invisibility	Camo	Armour	Shootback	Exoskeleton	Explosive/ Reactive Armour	Energy containment structure	IM	Modular armour	Sacrificial blast paths	Limitate signal emittance	Dodge	Stand off distance	Hard cover	
Interface with energy source	Umbilical	Human energy	Battery	Solar	Fuel	Sails	Engine	Clockwork	Nuclear						
Receive command	Umbilical	Fibreoptics	Ethernet	Voice	Bluetooth	Wifi	Infrared	Cellular	Satelite	Remote Control	Laser guidance	Physical Control	Radio	Preprogrammed	AI
Move	Wheels	Legs	Skids	Hover	Wings	Propellor	Tracks	Engine	Jet	Air cushion	Kinetic fling	Rocket Motor	Burrow	Gravity	Rollers
Detect Mine	Camera	GPR	Metal Detection	Heat / Infrared	LiDAR	Probing	Initiate	Smell	AI recognition	Animals	Radar	Children / POW	Vibes	Ultrasonic	Sequential
Communicate location of mine	Initiate	Audio	Flag	Illumination	GPS	Paint	Flare	Mapping	Air tag	Satellite	Grid Reference	Stationary	Umbilical		
Clear Mine	Explosively - Initiate	Scoop	Move	Plough	Rake	Kinetic - Initiation	Heat - Initiation	Directed Energy	Push	Fling	Cover				
Be recoverable	Self disposed	Human	Animal	Homing Signal	Recovery interfaces	Controlled shut down modes	RFID tag	Illimination	Emergency Stop						
Be disposable	Recyclable	Modular	Launch at enemy	Self disposing	Burly	Incinerate	Compostable	Sell for parts	Reusable components	Intiate mine					

Figure D- 1 - Initial FMA

Function	Means														
Be deployed	Damage checks	Assembly	Preuse checks	Flatpack	Inflate	Foldable	Air droppable	One piece							
Survive desert environment	Reinforced frame	Ingress protection	Filtration	IR sensors	Sun shielding	temperature resistant materials	Heat reflective Coating	Sun cream	Phase change materials	Air vents	Air/ Liquid Cooling	Insulation	Expansion tolerant materials	Temperature Sensors	High ground clearance
Resist kinetic attack	Invisibility	Camo	Armour	Shootback	Exoskeleton	Explosive/ Reactive Armour	Energy containment structure	IM	Modular armour	Sacrificial blast paths	Limitate signal emittance	Dodge	Stand off distance	Hard cover	
Interface with energy source	Umbilical	Human energy	Battery	Solar	Fuel	Sails	Engine	Clockwork	Nuclear	Power leads					
Receive command	Umbilical	Fibreoptics	Ethernet	Voice	Bluetooth	Wifi	Infrared	Cellular	Satelite	Remote Control	Laser guidance	Physical Control	Radio	Preprogrammed	AI
Move	Wheels	Legs	Skids	Hover	Wings	Propellor	Tracks	Engine	Jet	Air cushion	Kinetic fling	Rocket Motor	Burrow	Gravity	Rollers
Detect Mine	Camera	GPR	Metal Detection	Heat / Infrared	LiDAR	Probing	Initiate	Smell	AI recognition	Animals	Radar	Children / POW	Vibes	Ultrasonic	Sequential
Communicate location of mine	Initiate	Audio	Flag	Illumination	GPS	Paint	Flare	Mapping	Air tag	Satellite	Grid Reference	Stationary	Umbilical		
Clear Mine	Explosively - Initate	Scoop	Move	Plough	Rake	Kinetic - Initiation	Heat - Initiation	Directed Energy	Push	Fling	Cover				
Be recoverable	Self disposed	Human	Animal	Homing Signal	Recovery interfaces	Controlled shut down modes	RFID tag	Illimination	Emergency Stop						
Be disposable	Recyclable	Modular	Launch at enemy	Self disposing	Bury	Incinerate	Compostable	Sell for parts	Reusable components	Intiate mine					

Figure D- 2 - Low cost FMA

Function	Means														
Be deployed	Damage checks	Assembly	Preuse checks	Flatpack	Inflate	Foldable	Air droppable	One piece							
Survive desert environment	Reinforced frame	Ingress protection	Filtration	IR sensors	Sun shielding	temperature resistant materials	Heat reflective Coating	Sun cream	Phase change materials	Air vents	Air/ Liquid Cooling	Insulation	Expansion tollerant materials	Temperature Sensors	High ground clearance
Resist kinetic attack	Invisibility	Camo	Armour	Shootback	Exoskeleton	Explosive/ Reactive Armour	Energy containment structure	IM	Modular armour	Sacrificial blast paths	Limitate signal emittance	Dodge	Stand off distance	Hard cover	
Interface with energy source	Umbilical	Human energy	Battery	Solar	Fuel	Sails	Engine	Clockwork	Nuclear						
Receive command	Umbilical	Fibreoptics	Ethernet	Voice	Bluetooth	Wifi	Infrared	Cellular	Satelite	Remote Control	Laser guidance	Physical Control	Radio	Preprogrammed	AI
Move	Wheels	Legs	Skids	Hover	Wings	Propellor	Tracks	Engine	Jet	Air cushion	Kinetic fling	Rocket Motor	Burrow	Gravity	Rollers
Detect Mine	Camera	GPR	Metal Detection	Heat / Infrared	LiDAR	Probing	Initiate	Smell	AI recognition	Animals	Radar	Children / POW	Vibes	Ultrasonic	Sequential
Communicate location of mine	Initiate	Audio	Flag	Illumination	GPS	Paint	Flare	Mapping	Air tag	Satelite	Grid Reference	Stationary	Umbilical		
Clear Mine	Explosively - Initiate	Scoop	Move	Plough	Rake	Kinetic - Initiation	Heat - Initiation	Directed Energy	Push	Fling	Cover				
Be recoverable	Self disposed	Human	Animal	Homing Signal	Recovery interfaces	Controlled shut down modes	RFID tag	Illimination	Emergency Stop						
Be disposable	Recyclable	Modular	Launch at enemy	Self disposing	Bury	Incinerate	Compostable	Sell for parts	Reusable components	Intiate mine					

Figure D- 3 - High tech FMA

Function	Means														
Be deployed	Damage checks	Assembly	Preuse checks	Flatpack	Inflate	Foldable	Air droppable	One piece							
Survive desert environment	Reinforced frame	Ingress protection	Filtration	IR sensors	Sun shielding	temperature resistant materials	Heat reflective Coating	Sun cream	Phase change materials	Air vents	Air/ Liquid Cooling	Insulation	Expansion tollerant materials	Temperature Sensors	High ground clearance
Resist kinetic attack	Invisibility	Camo	Armour	Shootback	Exoskeleton	Explosive/ Reactive Armour	Energy containment structure	IM	Modular armour	Sacrificial blast paths	Limitate signal emittance	Dodge	Stand off distance	Hard cover	Explosive storage
Interface with energy source	Umbilical	Human energy	Battery	Solar	Fuel	Sails	Engine	Clockwork	Nuclear						
Receive command	Umbilical	Fibreoptics	Ethernet	Voice	Bluetooth	Wifi	Infrared	Cellular	Satelite	Remote Control	Laser guidance	Physical Control	Radio	Preprogrammed	AI
Move	Wheels	Legs	Skids	Hover	Wings	Propellor	Tracks	Engine	Jet	Air cushion	Kinetic fling	Rocket Motor	Burrow	Gravity	Rollers
Detect Mine	Camera	GPR	Metal Detection	Heat / Infrared	LiDAR	Probing	Initiate	Smell	AI recognition	Animals	Radar	Children / POW	Vibes	Ultrasonic	Sequential
Communicate location of mine	Initiate	Audio	Flag	Illumination	GPS	Paint	Flare	Mapping	Air tag	Satelitte	Grid Reference	Stationary	Umbilical	Physical marker	
Clear Mine	Explosively - Initiate	Scoop	Move	Plough	Rake	Kinetic - Initiation	Heat - Initiation	Directed Energy	Push	Fling	Cover	Thermite			
Be recoverable	Self disposed	Human	Animal	Homing Signal	Recovery interfaces	Controlled shut down modes	RFID tag	Illimination	Emergency Stop						
Be disposable	Recyclable	Modular	Launch at enemy	Self disposing	Bury	Incinerate	Compostable	Sell for parts	Reusable components	Intiate mine					

Figure D- 4 - Final FMA

Appendix E – QFD 2

Design feature	Importance		Importance	Damage checks	Assembly	Tamper indicators	Flatpack	One Piece	ingress protection	ir sensor	temp resistant materials	temp sensors	high ground clearance	camo	stand off distance	explosive storage	umbilical	battery	solar	fiberoptics	remote control	propeller	gravity	GPR	Metal detection	sequential	grid reference	physical marker	burn threat article	homing signal	modular	sell for parts	reusable components	
Functionality																																		
Be deployed	531	10	53.07366	9	9	9	9	9	3	3		1				9	9	9	3	9	9	9					3			1	3		1	
Survive desert environment	270	10	26.96834	3	3	3			9	3	9	3	9			9		1				1												
Resist kinetic attack	225	10	22.50506		9								3	9	9	9					1									3	1		1	
Interface with energy source	485	10	48.486506	3	9	9		1	3	9		3			3		9	9	9	9	9	9	3		3	3	3	3	1	3	3	1		1
Receive command	499	10	49.876259	3	9	9			1	3	3	3			1		9	3	1	9	9	3			3	3	3	1	3	3	9			1
Move	518	10	51.807013	9	9	9			3	3		1	9		3		3	9	3	3	9	9	9	9	3	3	1	3	3	3	9			1
Detect Mine	432	10	43.193248	3	9	9			3	9	1	1			3		3	9	1	3	9	1			9	9	9	3					9	
Communicate location of mine	248	10	24.752361	3	9	9			3	9	1	1	9		3		9	9	1	9	9	1	9	3	3	9	9	9				9		
Clear Mine	282	10	28.186792	9	9	9			3	3	1	1	3		9	9	9	9	1	9	9	1	9				9	9	9	3	9			
Be recoverable	98	10	9.767171		3		3	3	3		3	3	3		9		3	3	3	3	3	3					3			9		3	3	
Be disposable	214	10	21.393176		3		3	3				1			1	3		3	3												1	9	9	

Figure E- 1 - QFD 2