

# OME Major Project

81MM MORTAR, PRIMARY CARTRIDGE ASSEMBLY – PROCESS  
IMPROVEMENTS USING A SYSTEMS ENGINEERING APPROACH  
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# Contents

|                                        |    |
|----------------------------------------|----|
| Abstract.....                          | 3  |
| 1 Introduction .....                   | 3  |
| 2 Literature review.....               | 3  |
| 2.1 Systems engineering .....          | 3  |
| 2.2 Human Factors .....                | 4  |
| 2.3 Safety review.....                 | 5  |
| 2.4 Conclusion.....                    | 6  |
| 3 Methodology.....                     | 6  |
| 3.1 Stakeholders.....                  | 6  |
| 3.2 Understanding the problem.....     | 8  |
| 3.3 Requirements gathering .....       | 8  |
| 3.4 Operational Requirement .....      | 9  |
| 3.5 Initial Requirements.....          | 9  |
| 3.6 Stakeholder requirements .....     | 10 |
| 3.7 Functional Requirements.....       | 11 |
| 3.8 QFD - Critical Functionality ..... | 11 |
| 3.9 Function Means Analysis.....       | 12 |
| 3.10 Pugh Matrix.....                  | 12 |
| 3.11 QFD – Critical Features.....      | 14 |
| 3.12 P-Diagram.....                    | 15 |
| 3.13 PFMEA .....                       | 15 |
| 3.14 Process Flow.....                 | 17 |
| 3.15 PCP .....                         | 18 |
| 4 Results .....                        | 18 |
| 4.1 Final Design .....                 | 18 |
| 4.2 Design Verification .....          | 20 |
| 5 Discussion.....                      | 21 |
| 5.1 Reflections.....                   | 21 |
| 5.2 Further Work.....                  | 22 |
| 6 Conclusion.....                      | 22 |
| 7 Appendix A .....                     | 23 |
| 8 References .....                     | 24 |

|                                                                            |    |
|----------------------------------------------------------------------------|----|
| Figure 1 Mortar Tail with Primary Cartridge & Augmenting Charges [3] ..... | 3  |
| Figure 2 Premature explosion of a Mortar Bomb [11].....                    | 5  |
| Figure 3 Mortar crew loading munition into launch tube [10] .....          | 5  |
| Figure 4 Stakeholder Affinity Diagram .....                                | 7  |
| Figure 5 Stakeholder Map.....                                              | 7  |
| Figure 6 Functional Flow Diagram .....                                     | 11 |
| Figure 7 QFD – Critical Functionality.....                                 | 11 |
| Figure 8 Function Means Analysis.....                                      | 12 |
| Figure 9 QFD - Critical Features .....                                     | 14 |
| Figure 10 Purposely damaged primary cartridge base .....                   | 14 |
| Figure 11 Tooling.....                                                     | 14 |
| Figure 12 Taguchi Diagram .....                                            | 15 |
| Figure 13 Process Flow Diagram .....                                       | 17 |
| Figure 14 Overall Equipment Design [24] .....                              | 18 |
| Figure 16 Tooling - Bottom View .....                                      | 19 |
| Figure 16 Tooling - Side View.....                                         | 19 |
| Figure 17 Tooling Head .....                                               | 19 |
| Figure 18 Mechanically Assisted Arm .....                                  | 19 |
| Figure 19 Electrical Cabinet & Control Panel .....                         | 20 |
| Figure 20 Project Plan .....                                               | 23 |
| Table 1 Root Cause.....                                                    | 4  |
| Table 2 Stakeholder Responsibilities .....                                 | 6  |
| Table 3 Stakeholder Map Prioritisation .....                               | 7  |
| Table 4 Types of Requirement .....                                         | 8  |
| Table 5 Initial Requirements .....                                         | 9  |
| Table 6 Stakeholder Requirements.....                                      | 10 |
| Table 7 Process Functionality.....                                         | 13 |
| Table 8 PFMEA .....                                                        | 15 |
| Table 9 Requirement Validation .....                                       | 20 |

| Abbreviations |                                                           |
|---------------|-----------------------------------------------------------|
| NGMS          | Next Generation Munitions Solution                        |
| HE            | High Explosive                                            |
| RSI           | Repetitive Strain Injury                                  |
| HSE           | Health & Safety Executive                                 |
| HRA           | Human Reliability Assessment                              |
| MOD           | Ministry of Defence                                       |
| PC            | Primary Cartridge                                         |
| QFD           | Quality Function Deployment                               |
| DOE           | Design of Experiments                                     |
| PFMEA         | Process Failure Modes & Effects Analysis                  |
| PCP           | Process Control Plan                                      |
| SAU           | Safety & Arming Unit                                      |
| FAT           | Factory Acceptance Testing                                |
| IAT           | Installed Article Testing                                 |
| SOP           | Standard Operating Procedures                             |
| ATEX          | Atmospheres Explosibles (Explosive Atmospheres Directive) |

## Abstract

The aim of this report is to analyse the existing primary cartridge assembly process at BAE Systems Glascoed using a hard systems engineering methodology. Various tools from the hard systems engineering approach were used to support and help develop a new process solution, with a final design created ready for submission to BAE Systems to become the new assembly process. The systems engineering approach has identified critical features and critical manufacturing steps, and allowed the team to create a robust design. A new process has been designed, approved, and is ready for installation as a result of this report.

## 1 Introduction

The recently awarded NGMS contract between the Ministry of Defence and BAE Systems has given the opportunity to invest in the manufacturing capability at the Glascoed site. This project is part of the commitment to invest in new technology and continue to deliver an essential capability to the armed forces [1]. The Glascoed site is generally a fill, assembly and pack facility for munitions. One of the products made there is the 81mm mortar bomb, of which there are different variants, but for this project the focus will be on the High Explosive (HE) variant.

The full production of the 81mm HE Mortar Bomb is spread out over a number of buildings on site. This project is going to focus on the final assembly building as a number of concerns have been identified, as shown below.

- Primary cartridge percussion caps have been found installed upside down
- Mortar bombs have been found with missing primary cartridges
- Primary cartridge assembly process could cause repetitive strain injury (RSI)
- Primary cartridges have gone through the process without being correctly torqued into the mortar tail
- Primary cartridge bases have been scratched, damaging the product information printed on the bottom

The concerns have all been raised with the primary cartridge, an essential part of the initiation train within the mortar bomb. The primary cartridge holds the primary explosives to initiate the product, and it also contains propellant to send the mortar bomb out of the firing platform. A second propellant is often used in the augmenting charges however these are add-ons rather than components of the primary cartridge and they allow the range of the mortar bomb to be increased. The white arrow in Figure 1 shows the primary cartridge installed into a mortar tail, this will be the main focus of this project.



*Figure 1 Mortar Tail with Primary Cartridge & Augmenting Charges [3]*

Whilst the assumption of updating a production line in 2023 would mean following the industry 4.0 standard, this is more difficult in a high hazard environment such as an explosive processing facility. However this does not stop us from aiming for industry 4.0 while remaining as safe as reasonably practicable.

The aim of this report is to document a systems engineering analysis of primary cartridge installation leading to the design of a new primary cartridge assembly process, ensuring that the safety and quality of the product is improved.

## 2 Literature review

### 2.1 Systems engineering

Systems engineering is defined as a methodical, multi-discipline approach for the design, realisation, technical management, operations, and retirement of a system [2]. The field of systems engineering helps to tackle the complex and interdisciplinary nature of engineering projects, providing a means to the successful realisation of our aims and objectives. Engineering projects, particularly in a large organisation such as BAE Systems can be very complex, consisting of personnel, software, hardware, regulations, processes and facilities [3]. From experience, the regulations and limitations imposed by the facilities available have a key impact on the success of a project and has often been forgotten until later on in a programme. The holistic approach of systems engineering will focus on requirements

gathering and designing the system within the constraints set by the project team, eliminating as many emergent issues as possible.

Systems engineering is an overarching term that can cover a range of methodologies and theories, two of which will be covered here, and they are the soft and hard systems engineering approach. Research has shown that the soft systems methodology is well suited to investigation of the problem, this could also be known as the 'bottom up' approach. When there is limited knowledge or evidence on the problem, soft systems provides a framework for debate and discussion to find out what the problem is before we go on to solve it [4].

Soft Systems Methodology attempts to foster learning and appreciation of the problem situation between a group of stakeholders rather than set out to solve a pre-defined problem [5]

Both hard and soft systems methodologies consider the problem to be a 'system', however the hard methodology applies more to the technical aspects of the system while soft emphasises the organisational aspects. To build on that statement, the hard methodology is more rigid and structured than the soft methodology that is generally more flexible and adaptable. The hard systems methodology optimises the design and implementation of a system if the problem is better known [4]. In contrast to the quote above, this projects sole purpose is to solve a pre-defined problem, it has a clear end goal and the process is well understood, most of the effort should be put into the thorough design of the system, therefore the hard systems approach is better suited to this scenario.

## 2.2 Human Factors

As stated previously, Industry 4.0 may be the goal, but there are limitations imposed by the fact it's an explosive processing facility, this means that it is highly likely the solution will still have human involvement. As well as the likely human involvement in the new process, we will look at the concerns raised in section 1 and give a possible root cause for each with the existing process.

*Table 1 Root Cause*

| Concern                                                                                               | Root Cause                     | Detail                                                                                                                                                                                                                                                                          |
|-------------------------------------------------------------------------------------------------------|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mortar bombs have been found missing their primary cartridges                                         | Human Error                    | Operator distraction could mean an operator incorrectly thinks they have installed the primary cartridge, some products have black primary cartridges installed into a black mortar tail, therefore making it difficult on a quick glance to identify if it has been installed. |
| Primary cartridge percussion caps have been found installed upside down                               | Human Error                    | When assembled in a previous process building, the percussion cap has been manually installed upside down.                                                                                                                                                                      |
| Primary cartridge assembly process could cause repetitive strain injury (RSI)                         | Process consequence            | Threaded primary cartridge is manually screwed into the mortar tail, 6 complete rotations with the possibility of processing over 1000 products per day.                                                                                                                        |
| Primary cartridges have gone through the process without being correctly torqued into the mortar tail | Human Error                    | Distractions in the facility might result in a miscount of which products have been torqued correctly before moving onto the next stage.                                                                                                                                        |
| Primary cartridge bases have been scratched, damaging the product information printed on the base.    | Human Error & Tool Performance | Human Error – Skill of the operator using the tool, could slip out of the locking indents and scratch.<br>Tool Performance – Previous pneumatic tool operated too quickly and could slip and severely scratch the product.                                                      |

As shown in table 1, 4 out of 5 concerns have a potential root cause of human error and the only concern that isn't caused by human error, is only a concern because of human involvement. Whilst every effort is taken to minimise the possibility of RSI with strict time schedules per operator on that station, if the process was automated then RSI wouldn't have been a concern at all. This essentially means that human involvement is the cause of all 5 concerns. Given this conclusion, human factors engineering should also play a key part in the design of the new system, regardless of how much human involvement there may end up being.

One of the main objectives of human factors engineering is to minimise the risk of design-induced human performance issues that may lead to major incidents, other adverse events and reliability issues. This is particularly relevant in this environment as the potential major incidents could be fatal, not only to the operator but to anyone in the surrounding area. It can sometimes be difficult to separate system design error from human error unless a thorough investigation is carried out. It can also be common among industry to automatically assume something is human error if there isn't much known about the incident. Nancy Leveson has stated that even when a system becomes highly automated, the operator is often at the mercy of the system design and operational procedures [6]. In the Glascoed scenario, if not through general human error, it would mostly match up to the operational procedures rather than system design, however the new process introduces the new risk of the system design introducing human performance issues. To address this, experienced and inexperienced operators should be stakeholders in the design of the new system, as they'll be familiar with any procedural downfalls, and may have insight to the downfalls of potential new designs.

To determine the likelihood of genuine human error contributing to a possible incident, a Human Reliability Assessment could be conducted. The HSE has done a study of 72 different HRA methods to confirm their validity and suitability for use within the major hazard industry. Of these, 35 were investigated in more detail, and a final 18 were validated as being appropriate for high hazard industry, some of these have relevance specified to the nuclear industry, but there are still a number to choose from [7].

To conclude, although human factors may be what the project is trying to move away from with an automated solution, it is still a necessary consideration, ensuring that whatever the solution may be, works in harmony with any human operators and avoids producing unwanted emergent problems.

### 2.3 Safety review

Whilst every effort is taken to ensure ammunition is as safe as possible, the obvious end goal of a munition is to deliver its defeat effect, this means that it essentially needs to become as unsafe as possible when required [8]. To do this, there can be various safety and arming mechanisms in place to prevent unwanted detonation, in heavy artillery, this could be a spin force, coupled with a minimum distance/time. Most artillery systems require a breach to be sealed between loading the munition and starting the initiation train, this gives the user time to move away from the weapon system and also a barrier between the users and munition itself. A severe disadvantage of the 81mm mortar system is the proximity of the user to the munition, and the lack of protection provided to the crew. As shown in Figure 3, the mortar crew is directly next to the weapon system, and the time between the crew loading the munition and it initiating is only determined by the length of the tube. Once the mortar hits the bottom, a pin hits the primary cartridge percussion cap and the mortar is set off.



Figure 3 Mortar crew loading munition into launch tube [10]



Figure 2 Premature explosion of a Mortar Bomb [11]

There have been incidents with the mortar system, regardless of calibre, where the crew is injured or killed due to a mortar detonation while still inside the barrel. One of these incidents came in 2013 on a live firing exercise in Afghanistan, figure 2 is the final picture taken by a military photographer, as a mortar bomb exploded inside the barrel and killed the photographer and 4 afghan soldiers. There is no public evidence found to definitively say what caused the explosion, but it is a relevant and stark reminder of the nature of the product at the centre of this project.

Evidence has been found against a second mortar incident that killed 7 U.S Marines and injured 8 more, the cause of the explosion was double loading [9]. Information couldn't be found on what safety and arming mechanisms were in place to prevent this type of accident, however the tail of the second mortar hitting the fuze of the first mortar is possible to have set off the high explosive filling and caused the accident. Human error was determined to be the cause of this accident, however it highlights the possibility of a double loading incident, and anything that can be done to prevent this is paramount to the safety of the crew.

Whilst this project cannot prevent a ‘human error’ scenario of double loading, there are critical design features of the primary cartridge that may increase the likelihood of a double loading leading to an ‘in-bore’ accident. These critical features will be discussed in detail later, but in short, the orientation of the percussion cap and presence of a non-conforming primary cartridge assembly could result in a mortar being loaded but not initiated. Due to the speed and stresses of loading in a conflict environment, a second mortar could be loaded into the launch tube while the first hasn’t initiated and result in a repeat of the U.S Marine incident.

## 2.4 Conclusion

To conclude this literature review, it has brought to light a number of points to bring forward, firstly is to adopt a hard systems thinking methodology. Secondly, throughout the design phase, the operators need to be considered as key stakeholders, alongside a competent human factors engineer to ensure the designed solution works symbiotically with the operator. Finally, the safety review has shown that care needs to be taken surrounding the critical features of the primary cartridge, evidently to ensure the safety of the mortar crew, and also to safeguard the production team while making the products.

# 3 Methodology

## 3.1 Stakeholders

The starting point for this project is to identify the stakeholders and what role they will play. This is to ensure the correct people are aware of the project from an approval point of view, and also to ensure that there is a strong group of individuals discussing and directing the project to an appropriate conclusion.

The stakeholders have been listed below with a brief description of their capacity within the project.

*Table 2 Stakeholder Responsibilities*

| Stakeholder Position   | Responsibility                                                                           |
|------------------------|------------------------------------------------------------------------------------------|
| Lead Engineer          | Lead the project work and liaise with supplier                                           |
| Manufacturing Engineer | Provide project checklist and assist with project work                                   |
| NGMS P&E Engineer      | Input Plant & Equipment knowledge and requirements                                       |
| Human Factors Engineer | Perform human factors assessment against designs                                         |
| Process Engineer       | Input process engineering knowledge and requirements                                     |
| Project Manager        | Keep track of timescales and liaise with the customer                                    |
| Engineering Manager    | Approve project work                                                                     |
| Buyer                  | Initiate contracts and maintain relationship between BAE Systems and potential suppliers |
| SHE Advisor            | Provide safety knowledge and requirements                                                |
| Supplier PM            | Manage the design & supply of equipment                                                  |
| Supplier Designer      | Design the equipment                                                                     |
| Process Manager        | Approve new process                                                                      |
| Process Leader         | Input operations knowledge and requirements                                              |
| Operators              | Input user knowledge and requirements, use the equipment once installed                  |
| Mechanical Fitters     | Provide maintenance knowledge and requirements                                           |
| Electrical Fitters     | Provide maintenance knowledge and requirements                                           |
| Glascoed Stores        | Assist in equipment delivery                                                             |
| MOD Management         | Monitor project progress and conformity                                                  |
| End User               | Not required as there is no product change                                               |
| Logistics              | Not required as there is no logistical change                                            |

The list of stakeholders above needed to be sorted into groups that all have common interests in the project, this makes it clearer to organise the requirements, and prioritise them. It may be that not all requirements are absolutely essential, and they may be difficult to meet so being able to group and prioritise allows the team to take a wider view of the project and should meet as many criteria as possible. Following the systems engineering 7+-2 rule, the stakeholders have been collated into 7 groups.

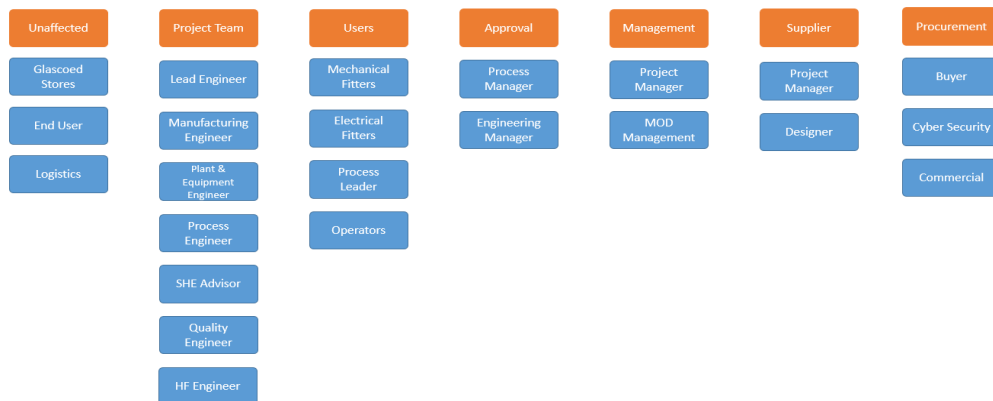


Figure 4 Stakeholder Affinity Diagram

From the seven groups of stakeholders, they need to be providing or taking something from the project, the stakeholder map below shows the interactions between groups. It may seem like the project team should be the number one priority as they have the most interactions with all other groups, but that's the nature of the project. The project teams responsibility is to communicate with all stakeholders and drive the project forward, poor communication from the project team would result in severe delays or a poor final solution.

Table 3 Stakeholder Map Prioritisation

| Priority | Group        | Justification                                                                                                     |
|----------|--------------|-------------------------------------------------------------------------------------------------------------------|
| 1        | Management   | Customer initiated requirement therefore their needs are the priority that must be met                            |
| 2        | Users        | The users must be happy to use the equipment and see the benefit otherwise they will deviate from the process     |
| 3        | Project Team | Main source of requirements development                                                                           |
| 4        | Supplier     | Must identify limitations and capabilities of the supplier to ensure the design is possible, reliable and optimal |
| 5        | Approval     | Approvals team will only be providing feedback (if necessary) on work already completed and final approval        |
| 6        | Procurement  | No value added to the project itself besides being a required department to procure the equipment                 |

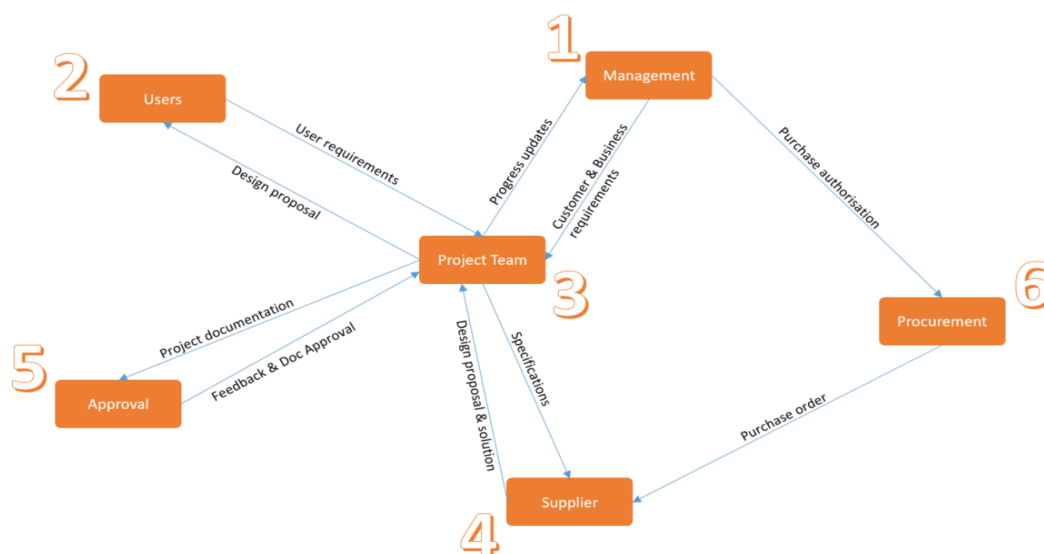


Figure 5 Stakeholder Map

### 3.2 Understanding the problem

To design a good system, we must first understand the problem fully, while the general purpose of the problem is understood, it would be easy to fall into the trap of designing what seems to be a great solution but in reality it isn't. The first step of the project was to perform a Gemba visit with a few of the key stakeholders. A process observation was made and notes taken down as to the functions of the system, as well as speaking to the operators to ask what their views were on the current and a potential new system.

The key point that stuck out from the operators is that this project has been done before, and not successfully. A pneumatic driver was implemented and whilst it reduced the possibility of repetitive strain injury, the speed was not controllable enough and the tooling often slipped out and then scratched the bases. Considering scratching is a key requirement from the MOD, this is something the project team must keep in mind when designing the system.

From discussions with the process leaders, it became clear that human factors is a major point of failure within any of our processes, regardless of how robust a process might be, you need to predict and eliminate possibilities of deviation from the process, both for quality and safety reasons.

### 3.3 Requirements gathering

Requirements are a formal statement of needs and expectations, using the systems engineering methodology. Requirements gathering is an essential part of the design process, without requirements you'll be guessing at what to design, and you won't know if you've designed it correctly anyway [10]. The requirements can be split into a number of categories, the types of requirements that may be gathered in this project are listed below, with an explanation of what they are and why they're important.

*Table 4 Types of Requirement*

| Requirement                   | What                                                                                              | Why                                                                                                                                                              |
|-------------------------------|---------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Operational                   | Overarching statement describing the capability of the system.                                    | To give clear direction for the project team and explain what the general goal is.                                                                               |
| Stakeholder                   | Requirements given by the various stakeholders of the project.                                    | To provide specific deliverables for the project, and they also are measurable targets to evaluate at the end of the project.                                    |
| Functional                    | Solution-free descriptive statements (verb-noun) of what the system will do.                      | To understand each step of the process and help determine how we achieve that particular function.                                                               |
| Non-Functional                | These are generally constraints on the system but do not say what the system will do.             | To determine how or how well something is done.                                                                                                                  |
| Non-Functional Performance    | These describe how well a functional requirement needs to perform, often contains a target value. | They give specific performance targets, usually from an operational point of view.                                                                               |
| Non-Functional Implementation | Solution based requirement, generally imposed by legislation or the customer.                     | Non-negotiable constraints/boundaries for the system to be designed within.                                                                                      |
| Non-Functional System         | These define constraints on the system as a whole rather than specifics.                          | General purpose requirements to take into consideration, can be split into further categories such as performance etc.. As long as they affect the whole system. |

### 3.4 Operational Requirement

To provide direction and structure to the project, an operational requirement should be agreed on by the project team. A famous operational requirement came from John F. Kennedy in 1961 is shown below and can be taken as a good standard of what an operational requirement should include.

*I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth.*

Kennedy's requirement is clear, time bound and includes a very important aspect of safety and care for his astronauts so taking this as a guide, the operational requirement for this project has been agreed as follows.

*To design a primary cartridge assembly process that minimises the likelihood of operator injury and maximises the quality of the product, and install the process no later than the 31<sup>st</sup> March 2023.*

### 3.5 Initial Requirements

As stated in the introduction, there have been concerns raised surrounding the primary cartridge, however these don't qualify as useable requirements throughout the project. They needed to be reworded to form a requirement as shown below.

Table 5 Initial Requirements

| Concern                                                                                                | Requirement                                                                              |
|--------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Primary cartridge percussion caps have been found installed upside down.                               | Ensure percussion caps are assembled in the correct orientation.                         |
| Mortar bombs have been found with missing Primary Cartridges                                           | Eliminate the possibility of mortar bombs leaving the process without primary cartridges |
| Primary cartridge assembly process could cause repetitive strain injury (RSI).                         | Eliminate the possibility of Repetitive Strain Injury.                                   |
| Primary cartridges have gone through the process without being correctly torqued into the mortar tail. | Ensure primary cartridges are correctly torqued into the mortar tail.                    |
| Primary cartridge bases have been scratched, damaging the product information printed on the bottom.   | Eliminate the possibility of the process causing damage to the product.                  |

It is well known in systems engineering that you rarely get a complete set of requirements, and the five that have been given are definitely not enough to run an effective project and deliver an appropriate solution. Further requirements will need to be drawn out of the existing process and through talking to various teams across the business including the often forgotten Gemba visits with a range of experienced and inexperienced operators. As suggested in the human factors section, including operators as key stakeholders should be an essential part of requirements gathering because there are few people that have better experience and insight to the process.

### 3.6 Stakeholder requirements

To begin scoping out a solution, further requirements need to be gathered from all stakeholders. Once this next stage of requirements has been gathered, then there are a number of different categories that the requirements can fall into. These requirements were gathered during a stakeholder meeting, after a preparation email was sent out to the stakeholders to consider what they wanted or needed from the system.

Table 6 Stakeholder Requirements

| Stakeholder  | Requirement                                                                              | Type |
|--------------|------------------------------------------------------------------------------------------|------|
| Management   | Eliminate the possibility of mortar bombs leaving the process without primary cartridges | NFS  |
|              | Must be installed before 31st March                                                      | NFS  |
|              | Ensure percussion caps are assembled in the correct orientation.                         | NFS  |
|              | Eliminate the possibility of Repetitive Strain Injury.                                   | NFS  |
|              | Ensure primary cartridges are correctly torqued into the mortar tail.                    | NFS  |
|              | Eliminate the possibility of the process causing damage to the product.                  | NFS  |
| Users        | Must be accessible for maintenance                                                       | NFS  |
|              | Power supply must use standard fittings and fixtures                                     | NFI  |
|              | Must be secured to the floor                                                             | NFI  |
|              | Must be capable of running a three shift pattern                                         | NFP  |
|              | Must have a reverse function                                                             | NFS  |
|              | Must be easy to hold                                                                     | NFS  |
|              | Complete a full pallet in <1 minute                                                      | NFP  |
| Project Team | Tooling should have minimum wear                                                         | NFP  |
|              | Machine must fit behind existing conveyor                                                | NFI  |
|              | Must be able to change programming on site                                               | NFS  |
|              | Must not allow cross threading                                                           | NFP  |
|              | Must be capable of data logging                                                          | NFS  |
|              | Must be able to process 54 bombs as a 'first off'                                        | NFS  |
|              | Safety indent above percussion cap                                                       | NFS  |
|              | Minimum IP44 rating                                                                      | NFS  |
|              | Must be painted Miami Blue                                                               | NFS  |
|              | Must be safe to operate                                                                  | NFS  |
|              | Tooling must be non-sparking                                                             | NFP  |
|              | Must register 4 processed bombs before release                                           | NFP  |
|              | Must have a controllable speed                                                           | NFP  |
|              | Unit must signal correct torque is reached                                               | NFS  |
|              | Must be UKCA marked                                                                      | NFS  |
| Supplier     | N/A                                                                                      | N/A  |
| Approval     | Must have a completed basis of safety                                                    | N/A  |
| Procurement  | N/A                                                                                      | N/A  |

It is very common for the majority of requirements from stakeholders to fall into the non-functional system category [10], this is because they think about the system and project as a whole, and what it needs to deliver in general terms rather than diving into the specifics.

### 3.7 Functional Requirements

Whilst the list of stakeholder requirements seems extensive at first glance, there is a very crucial set of requirements that have been missed completely, and these are the functional requirements. Without them, there is nothing to say how the system should behave and what operations it actually needs to follow. For example, the five requirements given in the introduction are not functional, they are a 'want' from the customer and the business but it gives no direction to the actual need of the process. If the team is to implement a successful replacement process, then the old process needs to be fully understood, and to understand that at a fundamental level, the functionality needs to be addressed. A functional requirement states how the system must behave, these should always be specified in a verb-noun format to show the system is doing something. After a visit to the production facility to observe the process in action, the existing functional requirements below were identified.

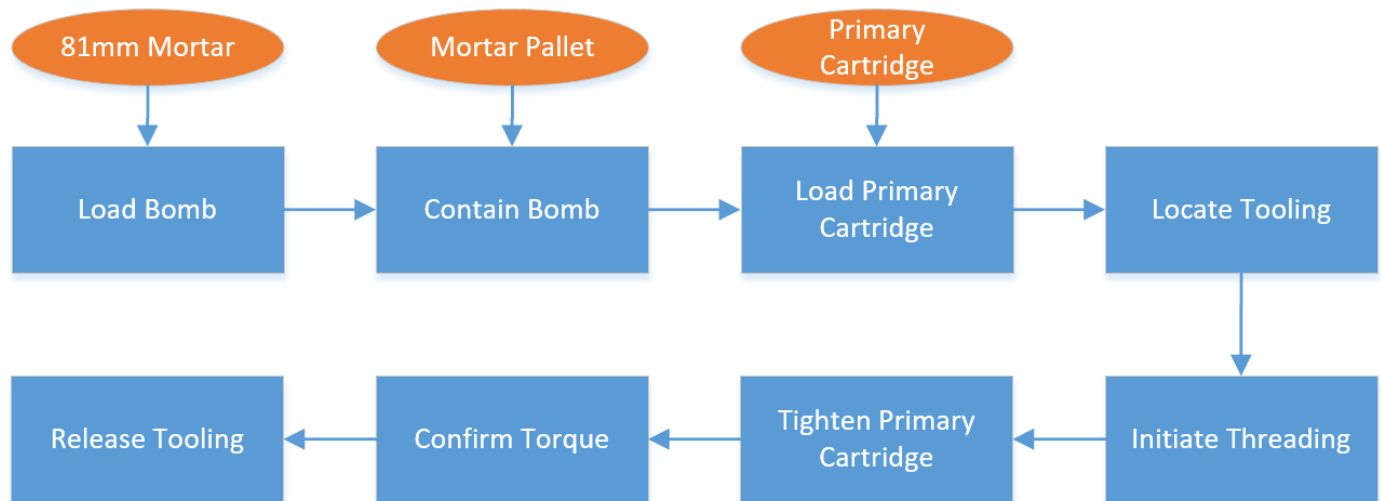


Figure 6 Functional Flow Diagram

Each of these requirements has carefully been written to avoid suggesting a solution, leaving the system open to interpretation from the range of stakeholders to specify solutions further into the project. It is possible to dive deeper into these requirements, and some of them will need further elaboration in order to meet the requirements of the product itself instead of the process, such as knowing the required torque value.

### 3.8 QFD - Critical Functionality

The QFD below has been used to determine the critical functionality, and it also serves as a level of requirements analysis. There are several rows or requirements that have no relationship with the functionality of the process, usually this could mean that it's an unnecessary requirement, or that there is some missing functionality. After analysing the blank rows, the decision has been made that they are still requirements, however some of them are for the project itself, or for the overall system and cannot be tied into the functionality/operations of the system. It does still identify some critical functionality within the system, and these have been identified as 'Initiate Threads, Tighten PC and Confirm Torque'. This has validated the project teams initial thoughts about what the critical functionality would be, as these are the interactions between the system and the actual assembly between the primary cartridge and the mortar bomb itself. These are also the interactions that would cause the concerns raised in the introduction.

| How                                                                    | Importance | Load Bomb | Contain Bomb | Load PC | Locate Tooling | Initiate Threads | Tighten PC | Confirm Torque | Release Tooling |
|------------------------------------------------------------------------|------------|-----------|--------------|---------|----------------|------------------|------------|----------------|-----------------|
| <b>Requirements</b>                                                    |            |           |              |         |                |                  |            |                |                 |
| Must be installed before 31st March                                    | 5          |           |              |         |                |                  |            |                |                 |
| Ensure percussion caps are assembled in the correct orientation        | 5          |           |              |         |                |                  |            |                |                 |
| Eliminate the possibility of Repetitive Strain Injury                  | 5          | 1         | 1            | 1       | 1              | 3                | 3          |                |                 |
| Ensure primary cartridges are correctly torqued into the mortar tail   | 5          |           | 1            | 1       | 3              | 0                | 0          |                |                 |
| Eliminate the possibility of the process causing damage to the product | 5          |           | 1            |         |                |                  |            |                |                 |
| Must be accessible for maintenance                                     | 5          |           |              |         |                |                  |            |                |                 |
| Power supply must use standard fittings and fixtures                   | 5          |           |              |         |                |                  |            |                |                 |
| Must be secured to the floor                                           | 5          |           |              |         |                |                  |            |                |                 |
| Must be capable of running a three shift pattern                       | 5          |           |              |         |                |                  |            |                |                 |
| Must have a reverse function                                           | 5          |           |              |         |                |                  |            |                |                 |
| Must be easy to use                                                    | 5          |           |              |         |                |                  |            |                |                 |
| Complete a full pallet in <1 minute                                    | 5          |           |              |         |                |                  |            |                |                 |
| Tooling should have minimum wear                                       | 5          |           |              |         | 1              | 3                | 0          | 1              |                 |
| Machine must fit behind existing conveyor                              | 5          |           |              |         |                |                  |            |                |                 |
| Must be able to change programming on site                             | 5          |           |              |         |                |                  |            |                |                 |
| Must not allow cross threading                                         | 5          |           |              |         | 1              | 1                | 3          | 1              |                 |
| Must be capable of data logging                                        | 5          |           |              |         |                |                  |            |                |                 |
| Must be able to process 54 bombs as a 'first off'                      | 5          |           |              |         |                |                  |            |                |                 |
| Safety indent above percussion cap                                     | 5          |           |              |         | 0              | 0                | 0          | 3              |                 |
| Minimum IP44 rating                                                    | 5          |           |              |         |                |                  |            |                |                 |
| Must be painted Hi-Lime Blue                                           | 5          |           |              |         |                |                  |            |                |                 |
| Must be safe to operate                                                | 5          | 1         | 1            | 3       | 3              | 3                | 1          | 1              |                 |
| Tooling must be non-sparking                                           | 5          |           |              |         | 0              | 1                | 3          |                |                 |
| Must register 4 processed bombs before release                         | 5          |           |              |         |                |                  |            |                |                 |
| Must have a controllable speed                                         | 5          |           |              |         |                | 3                | 0          | 1              |                 |
| Unit must signal correct torque is reached                             | 5          |           |              |         |                | 0                | 3          | 0              |                 |
| Must be UKCA marked                                                    | 5          |           |              |         |                |                  |            |                |                 |
| Must have a completed basis of safety                                  | 5          |           |              |         |                |                  |            |                |                 |
|                                                                        |            | 10        | 0            | 80      | 115            | 250              | 405        | 230            | 0               |

Figure 7 QFD – Critical Functionality

### 3.9 Function Means Analysis

Function Means Analysis is a highly structured approach to generating, selecting, and documenting system design concepts [11]. A group of stakeholders has been assembled to discuss potential solutions to the functionality of the system and three different criterion have been used to identify three potential solutions.

- **Low Cost** – The project has an overall budget, so cost needs to be a consideration when designing a new process, however it will always need to be weighed up against quality, safety and other factors.
- **High Quality** – The initial concerns of the customer are centred on the quality of the product, therefore quality should be a qualifying criteria.
- **Advanced Technology** – As part of the NGMS contract, and the companies value of being innovative, there should be a consideration made for modern technologies to improve the process.

| Activity Summary | Possible Ways of Performing Function               |                                                          |                                                                      |                                                                          |                                                                  |                                                         |
|------------------|----------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------|---------------------------------------------------------|
| Load Bomb        | Human Operator <span style="color: red;">●</span>  | Robotic Arm <span style="color: blue;">●</span>          | Pneumatic assisted lifting clamp <span style="color: blue;">●</span> | Electrically assisted lifting clamp <span style="color: green;">●</span> | Automatic conveyor delivery <span style="color: green;">●</span> |                                                         |
| Contain Bomb     | On-machine jig <span style="color: red;">●</span>  | Existing Pallet <span style="color: red;">●</span>       | Robotic clamp <span style="color: blue;">●</span>                    | Mechanical clamp <span style="color: green;">●</span>                    | Visual sensor clamp <span style="color: green;">●</span>         |                                                         |
| Load PC          | Human Operator <span style="color: red;">●</span>  | Robotic arm <span style="color: blue;">●</span>          | Hopper delivery <span style="color: green;">●</span>                 | Conveyor delivery <span style="color: green;">●</span>                   |                                                                  |                                                         |
| Initiate Threads | Human operator <span style="color: red;">●</span>  | Electric driver <span style="color: green;">●</span>     | Pneumatic driver <span style="color: blue;">●</span>                 | Hydraulic driver <span style="color: blue;">●</span>                     | Trigger controlled <span style="color: blue;">●</span>           | Pressure controlled <span style="color: blue;">●</span> |
| Locate Tooling   | Human Operator <span style="color: red;">●</span>  | Mechanically Assisted <span style="color: red;">●</span> | Robotic arm <span style="color: blue;">●</span>                      | Lowering lever <span style="color: green;">●</span>                      | Vision system <span style="color: green;">●</span>               |                                                         |
| Tighten PC       | Torque Wrench <span style="color: red;">●</span>   | Hand Tighten <span style="color: blue;">●</span>         | Electric driver <span style="color: blue;">●</span>                  | Pneumatic driver <span style="color: red;">●</span>                      | Hydraulic driver <span style="color: green;">●</span>            | Auto control <span style="color: green;">●</span>       |
| Confirm Torque   | Audio indicator <span style="color: red;">●</span> | Visual indicator <span style="color: blue;">●</span>     | Kinetic indicator <span style="color: red;">●</span>                 | Automatic stop <span style="color: green;">●</span>                      |                                                                  |                                                         |
| Release tooling  | Manual release <span style="color: red;">●</span>  | Automatic release <span style="color: blue;">●</span>    |                                                                      |                                                                          |                                                                  |                                                         |

Figure 8 Function Means Analysis

### 3.10 Pugh Matrix

| Requirements                                                            | Existing Process | Low Cost | High Quality | Advanced Technology | Combined Solution |
|-------------------------------------------------------------------------|------------------|----------|--------------|---------------------|-------------------|
| Must be installed before 31st March                                     | 0                | 2        | -1           | -2                  | 2                 |
| Ensure percussion caps are assembled in the correct orientation.        | 0                | 0        | 0            | 0                   | 0                 |
| Eliminate the possibility of Repetitive Strain Injury.                  | 0                | 1        | 2            | 2                   | 2                 |
| Ensure primary cartridges are correctly torqued into the mortar tail.   | 0                | 1        | 2            | 2                   | 2                 |
| Eliminate the possibility of the process causing damage to the product. | 0                | -1       | 2            | 2                   | 2                 |
| Must be accessible for maintenance                                      | 0                | -1       | -1           | -2                  | -1                |
| Power supply must use standard fittings and fixtures                    | 0                | 0        | -1           | -2                  | -1                |
| Must be secured to the floor                                            | 0                | 0        | 0            | 0                   | 0                 |
| Must be capable of running a three shift pattern                        | 0                | 0        | 0            | 0                   | 0                 |
| Must have a reverse function                                            | 0                | 1        | 2            | 2                   | 2                 |
| Must be easy to use                                                     | 0                | 1        | 2            | 2                   | 2                 |
| Complete a full pallet in <1minute                                      | 0                | 1        | 1            | 1                   | 1                 |
| Tooling should have minimum wear                                        | 0                | -1       | 1            | 1                   | 1                 |
| Machine must fit behind existing conveyor                               | 0                | 0        | 0            | -2                  | 0                 |
| Must be able to change programming on site                              | 0                | 0        | 0            | 0                   | 0                 |
| Must not allow cross threading                                          | 0                | -1       | 1            | -1                  | 1                 |
| Must be capable of data logging                                         | 0                | 1        | 2            | 2                   | 2                 |
| Must be able to process 54 bombs as a 'first off'                       | 0                | 0        | 0            | 0                   | 0                 |
| Safety indent above percussion cap                                      | 0                | 1        | 1            | 1                   | 1                 |
| Minimum IP44 rating                                                     | 0                | 0        | 0            | 0                   | 0                 |
| Must be painted Miami Blue                                              | 0                | 0        | 0            | 0                   | 0                 |
| Must be safe to operate                                                 | 0                | -1       | 1            | 2                   | 1                 |
| Tooling must be non-sparking                                            | 0                | 0        | 0            | 0                   | 0                 |
| Must register 4 processed bombs before release                          | 0                | 0        | 1            | 1                   | 1                 |
| Must have a controllable speed                                          | 0                | -1       | 2            | 2                   | 2                 |
| Unit must signal correct torque is reached                              | 0                | 0        | 2            | 2                   | 2                 |
| Must be UKCA marked                                                     | 0                | 0        | 0            | 0                   | 0                 |
| Must have a completed basis of safety                                   | 0                | 0        | 0            | 0                   | 0                 |
| Total                                                                   | 0                | 3        | 19           | 13                  | 22                |

Figure 9 Pugh Matrix Data

|                         | Low Cost              | High Quality        | Advanced Technology         | Combined Solution     |
|-------------------------|-----------------------|---------------------|-----------------------------|-----------------------|
| <b>Load Bomb</b>        | Human Operator        | Robotic Arm         | Automatic Conveyor Delivery | Human Operator        |
| <b>Contain Bomb</b>     | Existing Pallet       | Robotic Clamp       | Visual Sensor Clamp         | Existing Pallet       |
| <b>Load PC</b>          | Human Operator        | Robotic Arm         | Conveyor Delivery           | Human Operator        |
| <b>Initiate Threads</b> | Human Operator        | Pressure Controlled | Electric Driver             | Human Operator        |
| <b>Locate Tooling</b>   | Mechanically Assisted | Robotic Arm         | Vision System               | Mechanically Assisted |
| <b>Tighten PC</b>       | Pneumatic Driver      | Electric Driver     | Auto Controlled             | Electric Driver       |
| <b>Confirm Torque</b>   | Kinetic Indicator     | Visual Indicator    | Automatic Stop              | Visual Indicator      |
| <b>Release Tooling</b>  | Manual Release        | Automatic Release   | Automatic Release           | Automatic Release     |

Figure 10 Pugh Matrix Options

Various concept analysis tools could be used within the systems engineering boundary, one of which was the BAE Systems Figure of Merit model however the Pugh matrix has been used as it is familiar to the project team [12]. Using the Pugh Matrix, it is quickly seen which option has scored highest against both the stakeholder requirements, as well as the existing process as the 'control' option. They are assessed with a score from -2 to +2 to show whether the

chosen solutions perform better or worse than the control option. The results show that the solution chosen the 'High Quality' criteria has scored the highest, this could have been expected as the requirements are centred on quality issues but it is valuable to have confirmation that the requirements are being met. As discussed in a previous report written by the author, the Pugh Matrix doesn't have to give you the correct solution, but can be used to inform an additional combined solution [13]. This is beneficial as it allows consideration against the scoring for each requirement across all solutions and by having a discussion around them, we can reach a 'best of the best' solution while taking into account any restrictions that may not be listed in the requirements, such as cost.

The standard and expected view on process improvements may be that they should be more technologically advanced and move towards Industry 4.0, however the explosive nature of the business makes that difficult. Through the discussions it became clear that making everything as automated and new as possible didn't positively contribute to meeting the criteria. The Industry 4.0/automated focus was mainly put on the critical functionality of the process as this is where the process has shown the concerns that need addressing the most.

*Table 7 Process Functionality*

| Function         | Solution              | Justification                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|------------------|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Load Bomb        | Human Operator        | Loading the bomb is not a cause of any concerns raised to initiate the project. Both other solutions are very expensive, and it doesn't add enough value to the process to be a reasonable consideration.                                                                                                                                                                                                                                          |
| Contain Bomb     | Existing Pallet       | Containing the bomb is also not the cause of any concern, and the 81mm assembly process uses the existing conveyor for subsequent processes. This means that changing to any of the other options is more likely to have a detrimental effect on the rest of the assembly line with no benefit to the concerns to be addressed.                                                                                                                    |
| Load PC          | Human Operator        | The Primary Cartridge is the component that contains the explosives, therefore extra care needs to be taken when handling them. Whilst the two other options remove the operator from handling them, they also add in electrical components that increase the risk of the operation. The design of the primary cartridge and orientation needed for assembly would also make either of the other two options very difficult.                       |
| Initiate Threads | Human Operator        | Initiating the threads is the second most critical functionality, and this is the most likely point that will cause cross threading. Avoiding cross threading is a stakeholder requirement and using 'human touch' is a much better and careful way of aligning the threads correctly due to the delicate nature of them.                                                                                                                          |
| Locate Tooling   | Mechanically Assisted | The tooling is where the concerns begin to come in, tooling being the culprit of scratching the product base, both in locating and in driving the threads down. By upgrading to a mechanically assisted tool, it gives a greater level of control and should lower the likelihood of contacting the primary cartridge incorrectly and causing damage. A robotic or vision system to align the tooling does not have a positive cost-benefit ratio. |
| Tighten PC       | Electric Driver       | An electric driver gives a much greater level of control, it comes with a higher price tag, both in itself and with the new power supply that will be needed in the building. However the pneumatic option has been tried before and the lack of control meant the primary cartridges were scratched regularly. The electric option also gives the chance to incorporate the automatic option when further research is done into the final design. |
| Confirm Torque   | Visual Indicator      | A visual indicator such as a green/red light is unmistakable. A kinetic indicator could be missed due to tool vibration or distractions in the building. The electric driver might allow multiple indicators to be included, the automatic stop may work alongside the visual indicator.                                                                                                                                                           |
| Release Tooling  | Automatic Release     | The automatic release should guarantee that the last contact made between the tooling and the product is controlled and will not cause damage unlike a manual release.                                                                                                                                                                                                                                                                             |

### 3.11 QFD – Critical Features

Another QFD has been done to determine where the critical features are made, by analysing the design features of the primary cartridge against the design solutions chosen in the Function Means Analysis. The score along the horizontal shows a critical feature, and the score along the vertical shows a critical process step. As with any QFD, the higher the score, the more critical the process step and feature is. If there are significant gaps in the matrix then they need to be looked into to check if they're valid. The design features listed in this QFD are specifically non-descriptive for security reasons.

The obvious takeaway is that the first two functions of the system have no relationship with any of the design features of the primary cartridge, this is to be expected as the primary cartridge is not in the process at this point. The mortar bomb body being loaded into the assembly station is essential for the process to start, but can be removed from the boundary of this process. The FMA hasn't altered the existing process steps and no new relationships have been introduced so from this point they will not be considered as part of the process.

| Process Features          | Importance | Human Operator |              | Existing Pallet |                  | Human Operator |            | Human Operator |                 | Mechanically Assisted |         | Electric Driver |         | Visual Indicator |         | Automatic Release |         |
|---------------------------|------------|----------------|--------------|-----------------|------------------|----------------|------------|----------------|-----------------|-----------------------|---------|-----------------|---------|------------------|---------|-------------------|---------|
|                           |            | Load Bomb      | Contain Bomb | Load PC         | Initiate Threads | Locate Tooling | Tighten PC | Confirm Torque | Release Tooling | Release               | Release | Release         | Release | Release          | Release | Release           | Release |
| Important design features |            |                |              |                 |                  |                |            |                |                 |                       |         |                 |         |                  |         |                   |         |
| Driver indents            | 5          |                |              |                 | 1                | 3              | 9          | 9              | 3               |                       |         |                 |         |                  |         |                   | 125     |
| Thread                    | 5          |                |              |                 | 9                |                | 9          | 9              |                 |                       |         |                 |         |                  |         |                   | 135     |
| Marking                   | 5          |                |              | 1               | 3                | 3              | 9          | 3              | 3               |                       |         |                 |         |                  |         |                   | 110     |
| Primer tube               | 5          |                |              | 1               |                  |                |            |                |                 |                       |         |                 |         |                  |         |                   | 5       |
| Crimp                     | 5          |                |              |                 |                  |                |            |                |                 |                       |         |                 |         |                  |         |                   | 0       |
| Percussion cap            | 5          |                |              | 1               | 1                | 9              | 9          | 3              | 1               |                       |         |                 |         |                  |         |                   | 120     |
|                           |            | 0              | 0            | 15              | 70               | 75             | 180        | 120            | 35              |                       |         |                 |         |                  |         |                   |         |

Figure 9 QFD - Critical Features



Figure 10 Purposely damaged primary cartridge base

For design features, the crimp has no relationship with the process, the positioning of it on the primary cartridge and the movement of loading the product into the mortar give a negligible possibility of damage, the primer tube is low scoring for the same reason as the crimp, but given its size and interaction with the mortar, it's more susceptible to damage so it does hold a relationship with the process function.

On the other side of the scale are three design features that hold strong relationships with the process, these being the thread, the driver indents and the marking in order of criticality. The thread is a recurring point of focus throughout this project, going back to the safety review and PFMEA, if there was a failure of the thread, then that could create a catastrophic situation for the end user. Ensuring the thread is clean and undamaged throughout the process is critical. The driver indents are next for criticality, the reasoning for this is the direct relation it has to one of the initial requirements expressed

by the customer. Damage to the product in figure 10 shows how the marking of the product can be rendered illegible, this is both a quality and safety issue. Without the marking, it cannot be guaranteed what product has been assembled into the mortar body which is extremely unsafe and brings many unknown possibilities into the products lifecycle. Damage is one of the specific problems this project is trying to solve so it's unsurprising it has come out as a critical feature for this project. The final feature for consideration here is the percussion cap. The percussion cap sits inside the void in the middle of the product in figure 10, it contains a primary explosive that is highly sensitive with a low F of I in comparison to the secondary explosive contained within the mortar bomb. The two functions that are strongest against this feature are locating the tooling and tightening. The tooling interacts with the driver indents and the existing process has a flat surface against the base of the primer, similar to the initial design shown in figure 11. This has identified a possible problem with the existing process and a future design solution. The existing process is manual, and if the operator slipped off the primary cartridge, the pins could then contact the percussion cap and set off the initiation train. Also if the surface was kept flat, if debris of some kind got stuck in between the primary cartridge and the tool, this could also cause an impact to initiate the product. The lead engineer identified this as a potential problem early on, and submitted a requirement of 'Safety indent above percussion cap' and this QFD has put a level of validation behind that requirement. The possibility of the operator dropping the tool on the cap has been remove as the new process is mechanically assisted and will not allow fast movement of the tool,



Figure 11 Tooling

as well as being spring loaded so once the operation is complete, the equipment will return to its natural position raised above the product.

### 3.12 P-Diagram

As the functionality solutions have been chosen at this point, they need to be analysed at another level to ensure the design going forward is created to ensure the process will perform at a robust optimum rather than just the optimum. Over the years a number of robust design concepts have been discussed, tracing back to the 1920's with Fisher & Yates developing the statistical Design of Experiments (DOE) approach for agricultural applications and more recently in the 1950's and 60's with Dr Genichi Taguchi building the foundations of robust design for producing high quality products [14]. Using the teachings of Dr Genichi Taguchi, we can assess the robustness of a design, as shown in the graph in figure 12. The green plane will be the accepted tolerance or minimum performance level, the peak of the graph will be where the process is performing at its best, however there is a sharp drop off surrounding it where it would be easy to fall below the minimum performance requirement. The centre of the red patch is a robust optimum, being above the minimum level so it still meets the customers' expectations, while having space around it so if there is a level of variation, it is less likely to drop off so sharply below the green plane [15]. To identify the possible variations, a Parameter Diagram can be used and it is designed to split the variation into three different categories, signal factors, noise factors and control factors. A P-Diagram will be done internally for each functional requirement of the system to identify where the noise in the system may come from, and this can also help feed into the PFMEA as the noise could also be a potential cause of failure.

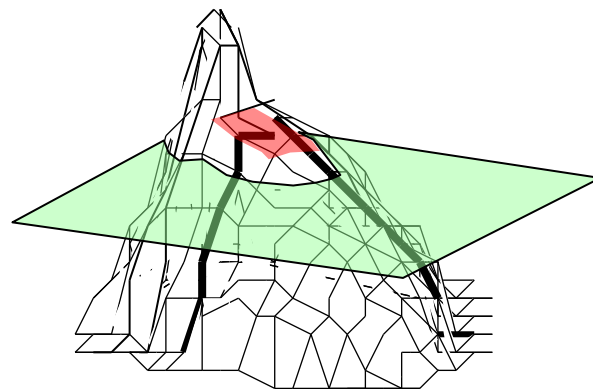


Figure 12 Taguchi Diagram

The reason for using a P-diagram is that by using the robust design theory, the quality of a product can be improved by minimising the effect of variation without eliminating the causes. A product or process is said to be robust when it is insensitive to the effects of sources of variability, even though the sources themselves have not been eliminated [16].

### 3.13 PFMEA

A PFMEA (Process Failure Modes & Effects Analysis) is a useful tool to support systematic analysis of the process to determine where the potential failures of the system will be. It can help to plan a robust control plan and implement robust control measures in the design and implementation stage [17]. The PFMEA below has taken the existing critical functionality from the existing process derived from the first QFD, and identifies where the failures are and what process controls exist, with the opportunity to recommend further actions and controls. The recommended actions here will feed directly into the design of the new system to ensure any potential failures are kept to a minimum, or eliminated if possible.

Table 8 PFMEA

| Process Function | Potential Failure Mode | Potential Effect(s) of Failure                                     | Sev | Potential Cause(s)/ Mechanism(s) of Failure         | Occur | Current Process Controls                                                              | Detect | Recommended Action(s)                                                                                 | Score |
|------------------|------------------------|--------------------------------------------------------------------|-----|-----------------------------------------------------|-------|---------------------------------------------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------|-------|
| Initiate Threads | No Initiate            | Process Delay – PC's not available to install<br><br>Misaligned PC | 5   | Scheduling/Supply chain issue<br><br>Operator error | 2     | Advanced planning of manufacturing schedule<br><br>Post-assembly gauge, 4-bomb pallet | 4      | Smart factory data feedback<br><br>Pre tightening physical check (gentle pull of all four assemblies) | 40    |
|                  | Under Initiate         | Misaligned PC – tightening process could create cross threading    | 5   | Contaminated threads<br>Operator error              | 3     | Visual check of threads                                                               | 4      | Go/no-go gauge to determine height of PC against mortar tail                                          | 60    |

|                |                       |                                                                                                                                                                   |   |                                                                         |   |                                                                                                         |   |                                                                                                                                                            |    |
|----------------|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|-------------------------------------------------------------------------|---|---------------------------------------------------------------------------------------------------------|---|------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
|                |                       |                                                                                                                                                                   |   |                                                                         |   |                                                                                                         |   | for minimum thread initiation                                                                                                                              |    |
|                | Over Initiate         | Process Delay – operator spending too long on a slower hand operation                                                                                             | 1 | Operator error – distraction                                            | 4 | Standard Operating Procedure                                                                            | 5 |                                                                                                                                                            | 20 |
|                | Unintended Initiate   | Product Safety – potential for misfire/double loading                                                                                                             | 5 | Operator error – PC installed too soon, plunger orientation not checked | 2 | Standard Operating Procedure 'shake' test                                                               | 4 | Check done in previous process building with operator work mark confirmation                                                                               | 40 |
|                | Inconsistent Initiate | Process Delay – operator having to check random products<br>Misaligned PC – tightening process could create cross threading                                       | 5 | Operator error<br>Operator error                                        | 2 | Standard operating procedure<br>Visual check of threads                                                 | 4 | Strict training to initiate 4 bombs at a time, right to left<br>Go/no-go gauge to determine height of PC against mortar tail for minimum thread initiation | 40 |
| Tighten PC     | No Tighten            | Process Delay – Lack of materials causes the process to stop or run slowly<br>Unsafe product – Energetics not contained leading to safety issues for the end user | 5 | Scheduling/supply chain issue<br>Operator error<br>Tool failure         | 1 | Advanced planning of manufacturing schedule<br>Gauge to determine if the PC is proud of the Mortar tail | 4 | Automated system feeding data back to the supply chain<br>Torque confirmation system                                                                       | 20 |
|                | Under Tighten         | Unsafe Product - Energetics not contained leading to safety issues for the end user                                                                               | 5 | Tool Failure                                                            | 3 | Calibration schedule                                                                                    | 4 | Visual torque confirmation/failure signal                                                                                                                  | 60 |
|                | Over Tighten          | Unsafe Product – Threads could be stretched leading to a weak assembly                                                                                            | 5 | Tool Failure                                                            | 3 | Calibration schedule                                                                                    | 4 | Automatic stop once torque value is reached                                                                                                                | 60 |
|                | Unintended Tighten    | Damaged Product                                                                                                                                                   | 4 | Operator error                                                          | 2 | Standard operating procedure – 4x bombs at a time                                                       | 4 | Engagement confirmation needed prior to tightening                                                                                                         | 32 |
|                | Inconsistent Tighten  | Process Delay<br>Unsafe Product                                                                                                                                   | 5 | Operator error<br>Tool failure                                          | 3 | Standard operating procedure – 4x bombs at a time                                                       | 4 | Visual torque confirmation/failure signal for all 4x bombs                                                                                                 | 60 |
| Confirm Torque | No Confirm            | Unsafe product                                                                                                                                                    | 5 | Tool Failure                                                            | 2 | Calibration schedule                                                                                    | 4 | Visual torque confirmation/failure signal for all 4x bombs                                                                                                 | 40 |
|                | Under Confirm         | N/A                                                                                                                                                               |   |                                                                         |   |                                                                                                         |   |                                                                                                                                                            |    |
|                | Over Confirm          | N/A                                                                                                                                                               |   |                                                                         |   |                                                                                                         |   |                                                                                                                                                            |    |
|                | Unintended Confirm    | Unsafe product                                                                                                                                                    | 5 | Tool Failure                                                            | 3 | Calibration schedule                                                                                    | 4 | Programmable driver with preventative maintenance schedule                                                                                                 | 60 |
|                | Inconsistent Confirm  | Unsafe product                                                                                                                                                    | 5 | Tool Failure                                                            | 3 | Calibration schedule                                                                                    | 4 | Programmable driver with preventative maintenance schedule                                                                                                 | 60 |

Firstly, there is a concerning amount of 5's in severity, meaning multiple fatalities, however this is in respect to the known incidents addressed in the safety review, it is no surprise that the critical features chosen for analysis here are showing high scores in that column. The common theme identified from the PFMEA is that any process function that has an effect on the joint between primary cartridge and mortar tail is a significant concern, this would be considered as a critical feature and this has been validated in the QFD in section 3.11. The threads holding the primary cartridge to the tail creates a seal for the primary explosives to be contained behind. If the seal fails, a number of scenarios could occur which takes us back to the safety review in the introduction. The containment allows the propellant to burn progressively as designed, if the energetic isn't fully contained this could lead to a slower burn [18], and although this is still a significant amount of force being exerted, it could result in a slower launch leading to possible double loading.

The problem also comes with gases escaping through the threads rather than through the tail as designed, it could slow down the propulsion and be unsafe for the users. If the threads are damaged and the seal isn't strong enough, then the pressure generated by the propellant could shear this joint. The mortar bomb may still launch from the tube however it may not have the appropriate velocity to reach its target. This could be catastrophic, depending on where the mortar crew launch from, it is entirely possible the bombs land on friendly forces, or even civilians. Once the mortar has exited the tube, the primary cartridge has completed its function and the changes implemented by this project have no impact on the overall defeat effect. The detonation of the mortar bomb is out of our control as it's triggered entirely by the fusing mechanism, therefore ensuring the product leaves the tube as intended minimises the risk of it landing and detonating at an incorrect location. The mechanism will have its own safety and arming unit inside determining when it's safe for the mortar to detonate. This could be a certain gravitational requirement through setback, a minimum time/distance after launch or programmable electronics. This could limit the explosive consequence of the munition, however it is still a heavy projectile that could land on something or someone. To understand this problem fully, an additional modelling task could be completed to provide data behind how the criticality of the joint could affect the overall performance of the munition. Whilst the SAU mechanisms are outside of the boundary of this project and remain unaffected by the decisions made, the overall quality of the specific components involved can be maximised to ensure the safety of the users.

There is also a significant amount of operator error identified in the process, the new system will eliminate that from the Tighten PC and Confirm Torque functions. This will effectively eliminate any potential safety or quality issues caused by the 'still human' Initiate Threads step. To do this, the system should lock the pallet in place and not release it until it has seen the four correct torque values including minimum rotations to cover tightening the same product twice, or from reaching the torque prematurely due to cross threading. It is absolutely key that the confirm torque function is performed correctly and reliably to ensure that the possibility of an incident like this is eliminated, when coupled with various checks throughout the process, this is the final stage to say that critical feature is safe to use on operations. This information will directly feed into the system to be designed to ensure there is a capable process in place, and ideally traceable, to mitigate a worst case scenario, being able to trace the issue back to the product affected will save time, money and potentially lives.

### 3.14 Process Flow

The new primary cartridge assembly process has additional functionality to the original process so the functional flow model has been updated to a more thorough process flow to reflect this change.

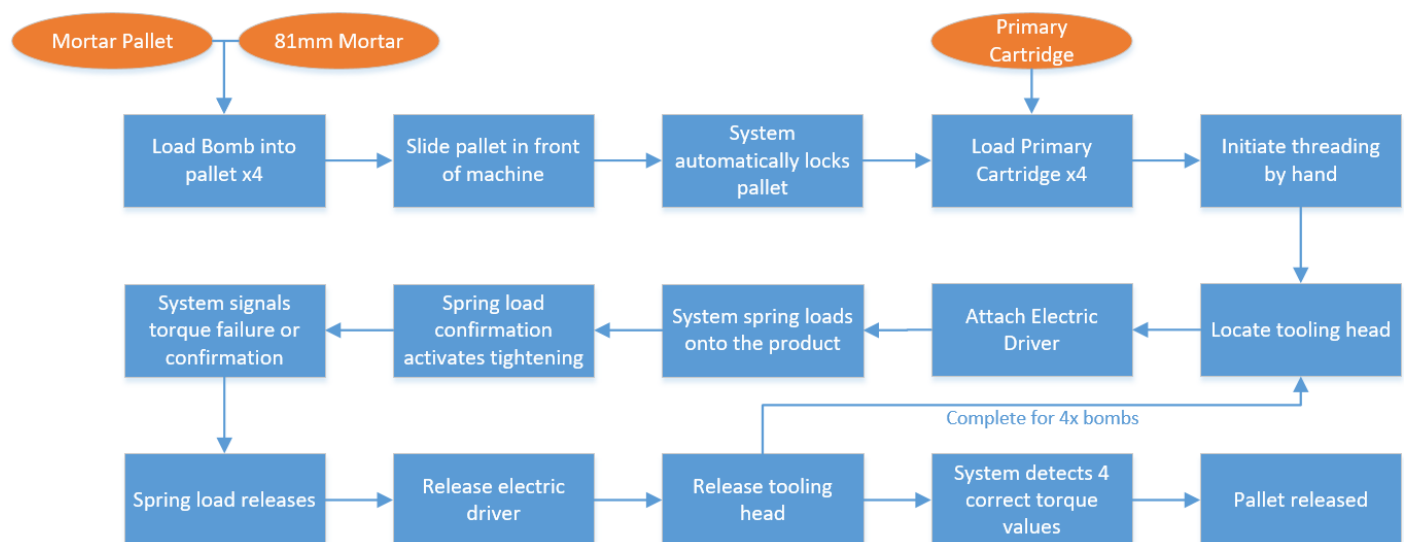


Figure 13 Process Flow Diagram

The updated process flow has included more detail than the original functional flow, but the new process has also added in extra steps, historically, extra steps are not received well by operators, however through communication and Gemba visits, the operational team understand they are necessary to maximise the quality and safety of the product, and they will be invited to the FAT to give their views and possible improvements on the process.

### 3.15 PCP

The PFMEA is a useful tool to show where failures might occur, however during production, there should be an overarching document that identifies where the process needs to be controlled, and how. The process control plan provides a summary description of the methods used to minimize process and product variation, and monitor the controls in place against process functionality [19]. By implementing these controls, the overall quality of the process can be maximised, and the PCP can also help in reducing waste, rework and any safety incidents. Strict control parameters that relate directly to the specification of the product allow the SOP's to be written in such a way that it should guarantee any product leaving the production line is acceptable and safe for the customer. The process control plan will follow the steps of the process flow, identifying the components involved, any specification limits, one of which would be the torque requirement. A process control plan has not been included in this report due to it containing specific data on munition production that is deemed sensitive, however it will be implemented alongside a full basis of safety for the new process.

## 4 Results

A possible route for the design was to purchase something 'off the shelf', a mechanically assisted arm is a reasonably standard piece of equipment, and the specific tooling to attach it to the primary cartridge would have to be specially designed. The benefit of this is firstly the lead time, it is much quicker to buy something that already exists, and generally it is likely to be cheaper as well. On the flip side, modifying something bought from a company might not meet our requirements as well as something designed from the ground up. The systems engineering methodology breaks down the process in such detail, that it would make more sense in this scenario, to design something that meets all of the requirements immediately rather than try and force someone else's product into the process. The results of this systems engineering analysis process have fed into the design shown in section 4.1, with an explanation of the key operability of each part.

### 4.1 Final Design

As stated in the previous section, the new process equipment shown below has been designed from scratch and has taken into account all outputs from the systems engineering study. Various improvements were made along the way, including separating the pneumatic and electrical components into individual cabinets to comply with regulations, as well as moving the HMI screen forward in comparison to its original location to make it easier for operators to use.

Conveyor – The conveyor and pallet will remain the same as changing it brings no benefit to the operation, and this ensures that it doesn't alter the subsequent operations. Pneumatic cylinders will be installed at the front and back of the pallets. This is to lock in the pallet and it will not release it until four correct torque values have been registered by the system. One of the noise factors brought out of the P-diagram was operator distraction, an operator could torque up a bomb, get distracted and then torque the same one again. To avoid the system registering four correct torques on potentially less than four bombs, a minimum torque angle requirement will also be programmed in. The cylinders will not release the pallet until the requirement of four minimum rotations and four correct torque values has been met.

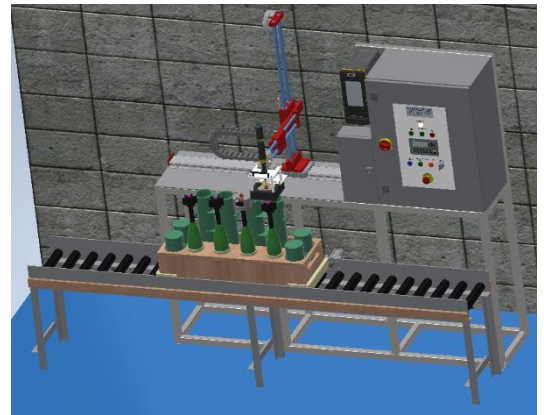


Figure 14 Overall Equipment Design [24]

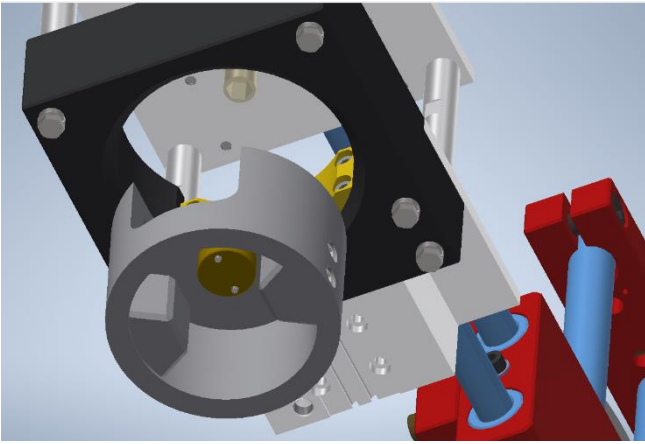


Figure 16 Tooling - Bottom View

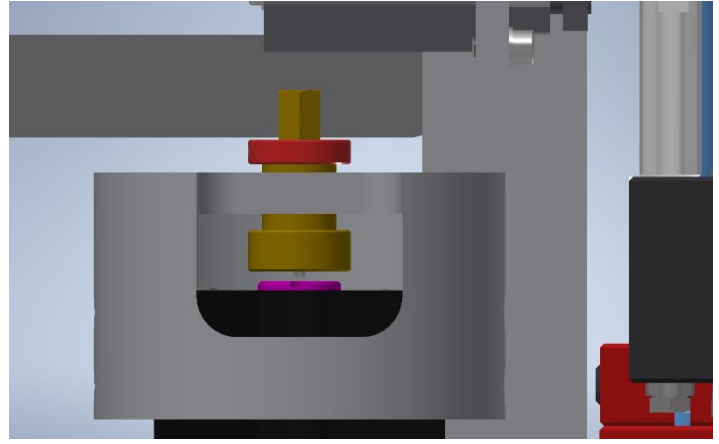


Figure 16 Tooling - Side View

Tooling – Damage has been caused to the product from the tooling slipping off, the two trapezoidal prisms machined into the tooling will slot into the fins of the mortar bomb, preventing any unwanted movement. These prisms must be manufactured from material softer than the mortar tail to avoid an emergent problem of potential damage introduced by the new process. The two pins on the tooling are where the interaction with the product is. A recurring issue is that if these pins wear down, then the tooling slips with the limited control of the human operator. This tooling setup holds the pins perfectly in line to minimise the potential of slipping, and the pins will be removable to ensure they can be regularly changed. This will be implemented into the preventative maintenance schedule for the system. There will also be a window machined into the tooling, to allow the operator to correctly line up the pins with the indents on the primary cartridge.

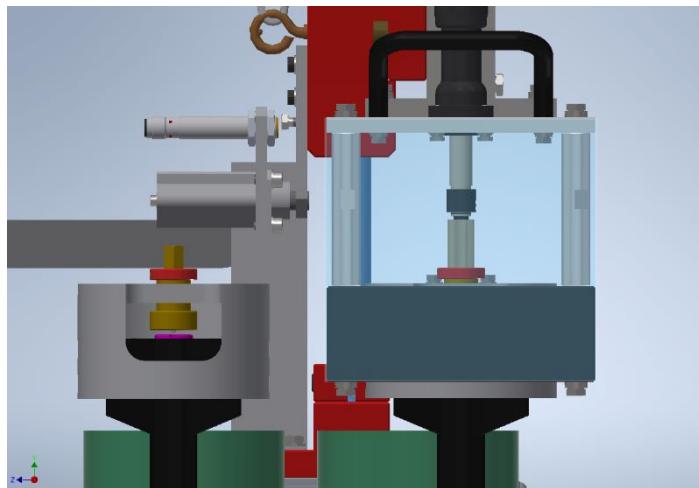


Figure 17 Tooling Head

Tooling head – the tooling head is connected directly to the electric driver, and will be lowered down onto the tooling itself. This is also spring loaded to ensure that once it connects to the tooling that has already been lined up with the primary cartridge, it is not possible to jump or slip out of the inserts. There will be clear guarding (shown in blue in figure 17) around the electric driver to comply with The Supply of Machinery Safety Regulations 2008.

Arm - As chosen in the Function Means Analysis, the 'Locate Tooling' functionality will be done by a mechanically assisted arm. The arm can move in the X, Y and Z directions, moved by the black handle on front of the tooling head, and can be limited in how far it can travel. The X-axis will be limited to the length of the pallet, the Y-Axis will be limited to the height required to perform the operation with no upper limit to ensure it can be moved out of the way when necessary. The Z-axis will be limited to 10mm in each direction as no more movement is required, this also minimises wear and the likelihood of making unwanted contact with the tooling or product.

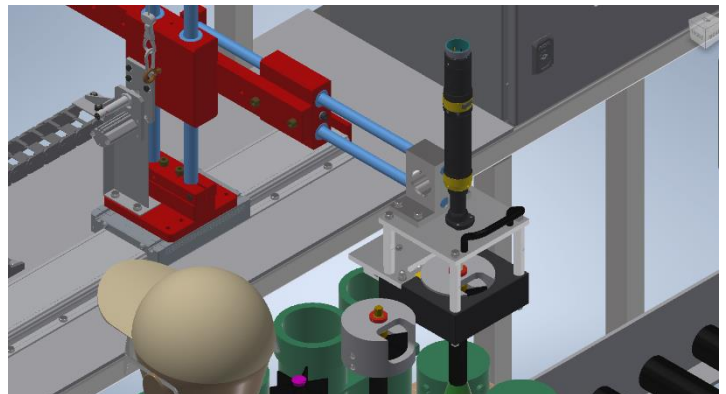


Figure 18 Mechanically Assisted Arm

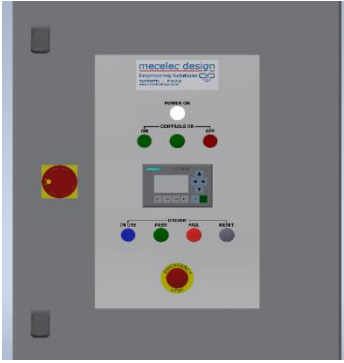


Figure 19 Electrical Cabinet &

Control system – As an electrical driver has been chosen, it needs a full electrical control cabinet, this will hold the electrical wiring for the system, but also acts as a basic display. Using visual indicators of a correctly torqued product, green for a pass, red for a fail and blue for in use. It also acts as the start-up procedure with a small screen for minor programming changes if necessary. There is an emergency stop to comply with ‘The Supply of Machinery (Safety) Regulations’ and a local electrical isolator switch to allow any maintenance to be carried out safely. The electrical cupboard itself will be locked with the standard electrician’s key to ensure only qualified and authorised personnel have access.

## 4.2 Design Verification

Verification and validation is an essential part of designing the new process, this report has covered the left hand side of the systems engineering V-model, which is the verification stage. Breaking down the problem into its requirements and conducting in depth analysis to create the solution. The validation comes through the dynamic testing of the system once the design is approved by the business. The requirements have been monitored throughout the design process, and the stakeholders have all been involved to produce the suggested system. At this point the requirements will be reviewed to prove the design meets the criteria and can formally be submitted for manufacture.

Table 9 Requirement Validation

| Requirement                                                             | Justification                                                                                                    |
|-------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| Must be installed before 31st March                                     | The design can meet this deadline                                                                                |
| Ensure percussion caps are assembled in the correct orientation.        | Not applicable to this building or assembly process                                                              |
| Eliminate the possibility of Repetitive Strain Injury.                  | Electrically powered tightening process                                                                          |
| Ensure primary cartridges are correctly torqued into the mortar tail.   | Pallet locked until 4 correct torques are reached using pneumatics cylinders                                     |
| Eliminate the possibility of the process causing damage to the product. | Spring loaded tooling prevents the slipping that leads to damage                                                 |
| Must be accessible for maintenance                                      | Control cupboards are easily accessible, electrical driver is removable                                          |
| Power supply must use standard fittings and fixtures                    | Confirmed                                                                                                        |
| Must be secured to the floor                                            | Asbestos survey completed and equipment designed to be secured to the floor                                      |
| Must be capable of running a three shift pattern                        | Confirmed – to be tested during FAT                                                                              |
| Must have a reverse function                                            | Confirmed – to be tested during FAT                                                                              |
| Must be easy to hold                                                    | Confirmed – to be tested during FAT                                                                              |
| Complete a full pallet in <1 minute                                     | To be tested during FAT                                                                                          |
| Tooling should have minimum wear                                        | Tooling made from appropriately hard material                                                                    |
| Machine must fit behind existing conveyor                               | Dimensions checked and confirmed                                                                                 |
| Must be able to change programming on site                              | Programming access enabled                                                                                       |
| Must not allow cross threading                                          | Reliant on operator training, torque confirmation to eliminate any cross threaded products reaching the customer |
| Must be capable of data logging                                         | Confirmed – to be tested during FAT                                                                              |
| Must be able to process 54 bombs as a 'first off'                       | Confirmed – to be tested during FAT                                                                              |
| Safety indent above percussion cap                                      | Supplier contacted to amend design to show indent, confirmed                                                     |
| Minimum IP44 rating                                                     | Confirmed                                                                                                        |
| Must be painted Miami Blue                                              | Confirmed                                                                                                        |
| Must be safe to operate                                                 | To be tested during FAT with operator involvement                                                                |
| Tooling must be non-sparking                                            | Confirmed                                                                                                        |

|                                                |                                            |
|------------------------------------------------|--------------------------------------------|
| Must register 4 processed bombs before release | Programming enabled                        |
| Must have a controllable speed                 | Confirmed – to be tested during FAT        |
| Unit must signal correct torque is reached     | Confirmed – to be tested during FAT        |
| Must be UKCA marked                            | To be confirmed on acceptance of equipment |
| Must have a completed basis of safety          | To be completed in due course              |

It can be noted that whilst not all of the requirements have been validated at this point, they are all verified in principle with one exception. The requirement on percussion caps was discussed early on, with potentials for a vision system to be installed to detect the orientation, however it was too expensive, and generally inappropriate for this process. The percussion cap into the primary cartridge assembly itself is conducted in a separate building earlier in production and this should be a project taken on in that building to ensure incorrect products aren't being sent further into the production line.

All other requirements have been met by the design of the system, however until a period of FAT has been conducted, they cannot be validated. Upon completion of an FAT programme designed by the stakeholders, many of the requirements can be validated, or additional work can be agreed with the supplier to improve the system and ensure it meets the requirements prior to being installed on site. A second level of testing under engineering control, IAT, will be completed at BAE Systems Glascoed to ensure nothing has changed and the system works correctly. IAT will then be followed by a period of formal commissioning, which will be a more in depth and managed by operations. This allows the operators to be trained on the system, and have supervision from the supplier and the engineering team to identify any emergence on a more intensive throughput.

## 5 Discussion

### 5.1 Reflections

Whilst a full PFMEA has been completed internally, the decision was made to assess the three critical functions identified in the first QFD, however on reflection, it would have been better to choose the three functions that have been altered in the Function Means Analysis table. This is because the new system upgrades those three functions completely, instead of the 'initiate threads' function which is still done by an operator albeit with some extra checks added to the process. The function that should have been assessed instead is the 'Locate Tooling' option as it relates to the damage concern. The initiate threads function is definitely worth considering as a safety option, however safety was not a concern expressed by either the customer or the business in section 1 so for the boundary of this report, the focus should be on the functions affected by the new system.

There were a number of difficulties throughout this project, one of which was losing a significant amount of time due to a change in cyber security requirements from the business, having a knock on effect to the implementation of the systems engineering methodology within the target timeline. This also meant following the original project plan was impossible. In hindsight, the Gantt chart should have been structured around regular meetings and milestones, with an attendance record of the stakeholders to ensure traceability and accountability of the process and decision making.

The Russia-Ukraine conflict has also had a significant impact on the project, with employee availability significantly reduced due to additional demand from the business. Recruitment on-boarding has a severe lag behind manufacturing demand therefore the stakeholders involved in this project have been stretched across other areas to fulfil the requirement from the MOD and any other conflict related requirement. To deal with this, meetings had to be shorter but more frequent to discuss the project and more responsibility for managing the project and making decisions fell to the lead engineer and senior manufacturing engineer.

The main aim of this report was to submit a design recommendation that has been created and analysed using a systems engineering approach. This aim has been achieved, a number of systems engineering tools have been used throughout this project and it has helped to highlight critical functionality and critical features of the product itself. Although the Primary Cartridge product design is outside of the boundary for this project, it was crucial to understand where that criticality is to ensure the process relating to it was given extra scrutiny and attention. In an ideal world, the product itself would go through a redesign, as the two indents used to tighten the primary cartridge are so small

and shallow, that any operation to tighten it is difficult. The proposed solution performs at its best to limit any potential slippage and this will be tested through a rigorous FAT, IAT and Commissioning schedule.

Every effort has been made using the systems engineering approach to ensure the new process will need no design alterations, however the FAT regime should highlight any minor changes that need to be made while still in the supplier's facility. Whilst redesign is expensive, this will be cheaper in comparison to a much larger expense to redesign or modify the equipment when it is on site in Glascoed. This is not only due to the additional logistics, but also the effect of indirect costs from a loss of production capability.

## 5.2 Further Work

Whilst the aim of this project have been achieved, there is an opportunity for future work to be done with the process. The limit of this report is to suggest a robust design to the business, the immediate next step is to perform a series of tests as mentioned in the previous chapter, install the equipment and handover to operations for full scale production. Alongside this will be a significant package of paperwork, including risk assessments, updated WASC, DSEAR, FERA, SOP's etc.. These among others will make up the full basis of safety to sign off the equipment as safe to operate and achieve its own certificate of manufacture.

Longer term plans could include updating the rest of the Mortar assembly process, starting with fuze assembly, this process is physically located next to this new primary cartridge process and is currently done on a large carousel. A better solution would be to incorporate it onto the existing conveyor, and use a similar semi-automated torque driver to secure the fuze. This was considered at the start of this project, however there is a level of complexity that exceeds the cost-benefit ratio at this time. A larger scale update would be transitioning to lean and smart manufacturing. There are several process stations in the building that require lifting the bombs into the station to be processed, and taken off again to move further into the production line. The building has the potential for the existing conveyor to be extended and flow throughout the building, if this could be achieved, then it will move the process towards lean manufacturing. With a new lean manufacturing layout, it would be easier to implement further smart factory improvements, including a series of automated assembly machines including capabilities such as stencilling, fuzing, packing and labelling. Of all the process buildings in BAE Systems Glascoed, this building would be an easier option to trial a smart factory setup due to a Category C ATEX rating, meaning automated machinery only needs to reach an IP44 level, reducing complexity and cost.

## 6 Conclusion

The design shown in section 4.1 is appropriate for submission to BAE Systems to replace the existing primary cartridge to mortar tail assembly process, with the confidence behind it from using the systems engineering approach that it's a robust solution to address the concerns raised by the business and customer. The project itself has encountered problems that have been addressed and overcome, with one requirement being deemed inappropriate for this project to cover, and unfortunately due to some of the points raised in the discussion, the March 31<sup>st</sup> deadline for installation cannot be met. The project management plan created on the conclusion of this design being approved is shown in Appendix A, however since it was created the timeline has slipped and this will be addressed with updates in the accompanying presentation and poster to this report. The systems engineering approach has been informative and has given the project team a structured approach and supporting evidence towards a certificate of manufacture. The literature review gave important areas of focus for the project, particularly safety, which were perhaps not the key requirements from the customer but needed to be kept in mind constantly for the project team. The human factors aspect of the project has been helpful in some of the decision making, but will become more prevalent in the further work, including the documentation, installation and training of the process. Overall the project has been deemed a success up to this point, with the machine being approved for purchase and manufacture, with plans in place for the installation and handover to production.

7 Appendix A

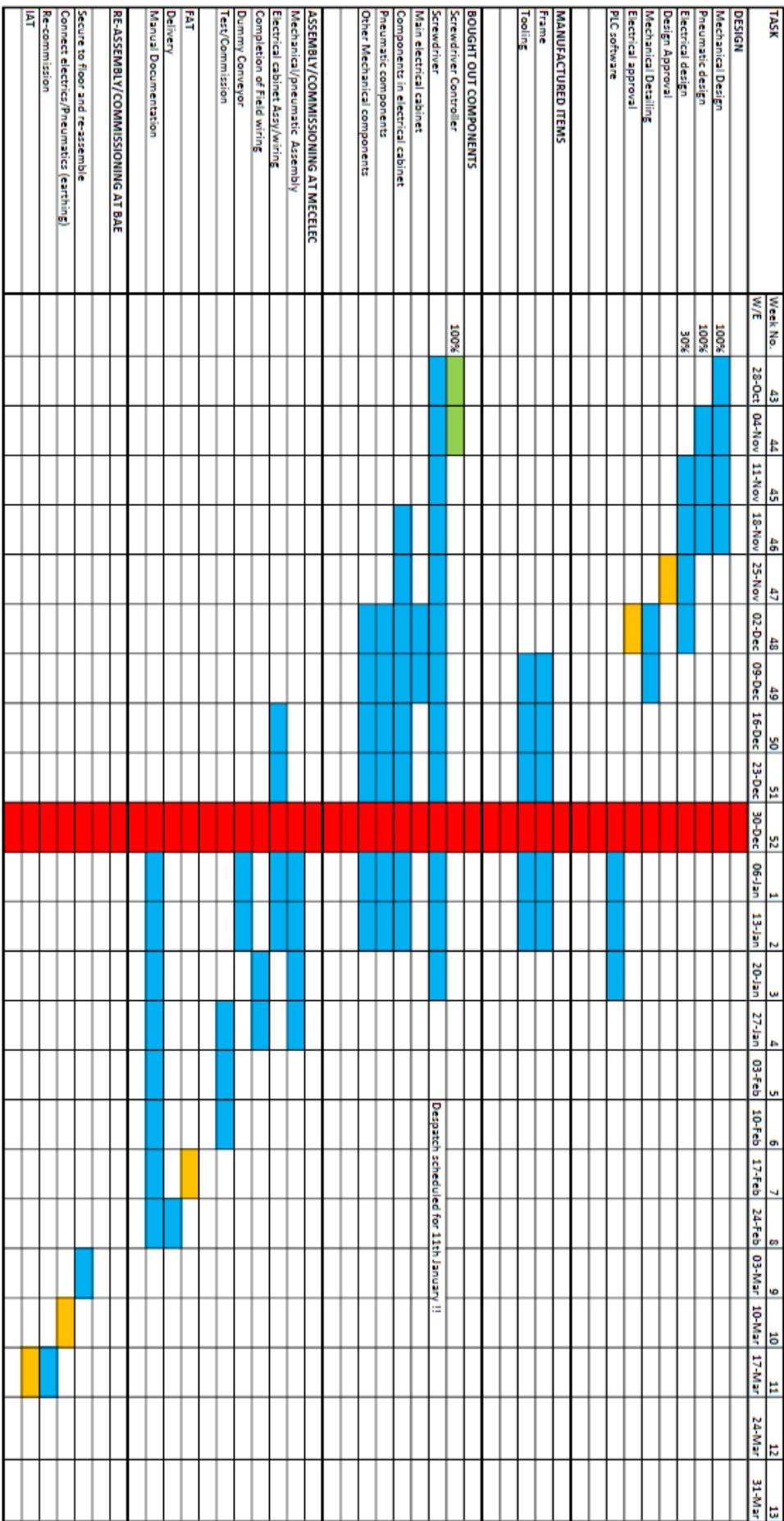


Figure 20 Project Plan

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