A Tailorable Framework of Practices for Maintenance Delivery

Engineering Doctorate

Innovation Report

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Abstract

Scope – This research focused on the development of a tailorable framework of practices for Maintenance Delivery (MD): i.e. a flexible business process design tool which was developed in order to resolve a series of specific gaps identified in the sponsor's Asset Management System (AMS).

Methodology – The framework was developed in two stages: firstly via a systematic review of existing MD practices from the literature in order to establish a preliminary version; this was then developed further via a Delphi study utilising the opinion of experts from industry to critique and improve the initial framework design.

Key Findings – The framework was implemented and tested in the sponsor company in order to demonstrate its ability to successfully improve MD practices across multiple sites in different industry contexts. A post-implementation assessment demonstrated significant improvement, sufficient to close all of the high-risk gaps that were originally identified.

Contribution to Industry – The framework covers the entire subject area of MD in detail and offers a wide range of optional practices throughout, complete with expert guidance to facilitate the decision-making process. This means it can be utilised by any business to design an effective MD process that is tailored to suit their specific context. Alongside a tailored MD process, the framework will also generate a fully aligned implementation specification for the supporting CMMS (Computerised Maintenance Management System), which is also tailored according to the same contextual requirements. This will enable the end user of the framework to procure, implement and configure a CMMS that has the complete range of functionality required to fully support their business requirements.

Innovation – A tailorable framework that is flexible enough to be utilised in many different industries is novel, because existing MD processes are generally designed for a single, specific case and cannot adapt to different contexts. The size and scope of the framework also validates the innovation claim – i.e. a series of flowcharts covering multiple AM subject areas, with 157 core process steps, 109 contextual options, and 30,000+ words of guidance. The fact that framework has already been successfully utilised to develop and implement an effective MD process in a very specific context (i.e. a maintenance-intensive, highly regulated nuclear site with a relatively small workforce) further strengthens the claim for innovation.

Acknowledgements

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List of Abbreviations

AM	Asset Management
AMS	Asset Management System
BOM	Bill of Materials
BSREC	Biomedical and Scientific Research Ethics Committee
CMMS	Computerised Maintenance Management System
EAM	Enterprise Asset Management
ERP	Enterprise Resource Planning (System)
FM	Facilities Management
GFMAM	Global Forum on Maintenance and Asset Management
GPS	Global Positioning System
ISO	International Organisation for Standardisation
KPI	Key Performance Indicator
MD	Maintenance Delivery
MM	Materials Management
MMM	Maintenance Manager’s Meeting
MRA	Maintenance Requirements Analysis
ONR	Office for Nuclear Regulation
PAS	Publicly Available Specification
PDCA	Plan, Do, Check, Act
RF	Requirements Framework
RFQ	Request for Information

STO	Shutdown, Turnaround or Outage
WO	Work Order

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1. Introduction

This report provides a comprehensive summary of an Engineering Doctorate (EngD) research project carried out between 2014 and 2018 at the University of Warwick, with a focus on the main findings and innovations delivered. Further details can be found in the accompanying EngD portfolio – i.e. a collection of submissions that present the entire research effort in detail (see Fig. 1 below).

1.1. *Portfolio Structure*

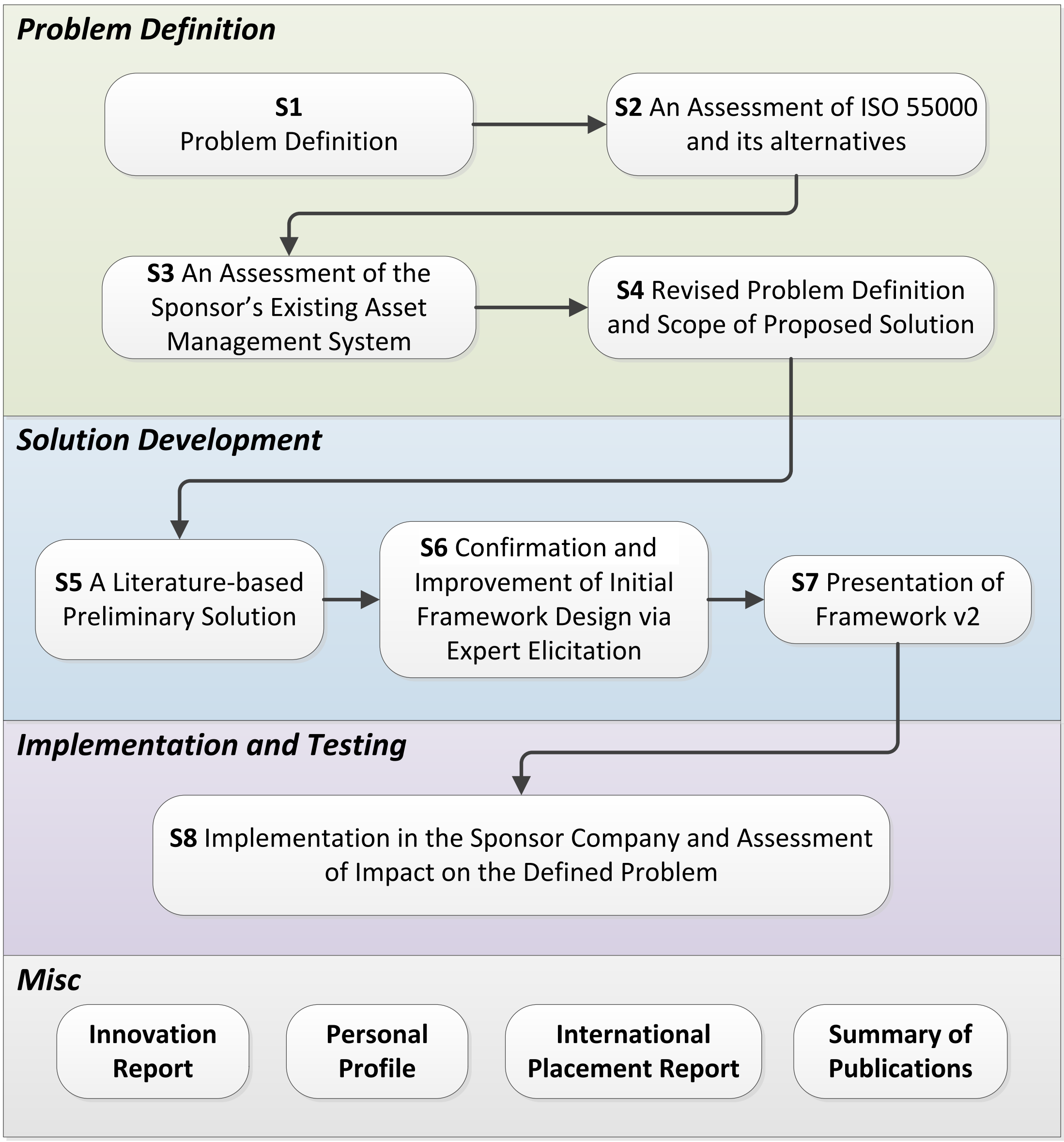


Fig. 1 – EngD Portfolio Structure and reading order of submissions

Brief highlights are provided below for each submission shown above in Fig. 1:

- **Submission 1: Problem Definition**
    - Provides a detailed background to the project by introducing the sponsor company and the principal research subject, Asset Management (AM).
    - Defines a problem faced by the sponsor – i.e. that their existing Asset Management System (AMS) will not be suitable for their newest manufacturing facility (currently under construction), because the plant is significantly different to their existing asset base. It hypothesises that the ISO 55000 standard (for AM systems) will be the most suitable framework on which to develop a new AMS.
    - In hindsight, this initial submission should have been named "Background". Whilst it does define a formal problem, this was later revised in Submission 4 after further investigation.

- **Submission 2: An Assessment of ISO 55000 and its Alternatives**
    - The hypothesis from Submission 1 was tested to determine if ISO 55000 was indeed the most suitable framework on which to develop the sponsor's new AMS.
    - An extensive literature search was carried out to identify all available alternatives to ISO 55000. They were then evaluated systematically in order to determine which was the most suitable framework in the sponsor's context. The conclusion was that ISO 55000 was the best available option.
    - An innovative new assessment tool was created in the process for assessing an AMS against the requirements of ISO 55000.

- **Submission 3: An Assessment of the Sponsor's Existing Asset Management System**
    - The assessment tool from Submission 2, supplemented by the results of an external audit (carried out by others), was utilised to assess the sponsor's existing AMS against the requirements of ISO 55000.
    - The aim was to identify which specific AMS components were deficient and by how much (i.e. the extent of the gaps). This was achieved by risk-assessing each of the gaps to determine their significance in the context of the sponsor's business.

- **Submission 4: Revised Problem Definition and Scope of Proposed Solution**
    - The intent of this submission was to utilise the findings from Submission 3 to define a more specific problem that would require an in-depth, research-based solution with a clear scope for innovation.
    - The most significant gap identified in Submission 3 was the business process for the planning and control of AM activities, particularly in a Maintenance context – from then on termed a "Maintenance Delivery" (MD) process. Several closely-related AM subject areas that were found to strongly interact with MD were also included within the research scope.
    - After sharing the assessment results from Submission 3 with the sponsor company, they requested a MD solution that would work for their entire business, rather than just for the new facility. Because each site operated in different contexts (i.e. in different countries with different external stakeholders and regulations, with different asset ages and technologies, with different organisational structures and cultures etc.), a flexible solution was proposed that could be tailored to suit any context – i.e. a framework of MD practices with multiple options available for selection, complete with expert guidance to enable the end user to develop their own tailored solution based on their context (from then on, the project title was changed to *"A Tailorable Framework of Practices for Maintenance Delivery",* and a completed framework became the main project deliverable).
    - An additional finding from the literature showed that in a MD context, the functionality of the supporting IT system (i.e. the CMMS – Computerised Maintenance Management System) is a critical enabler that must be closely aligned to the business process, or that process will not function effectively. In practice, CMMS software was often found to be poorly implemented due to a lack of clear requirements, resulting in poor MD performance (see section 5.3.1 for more details and references). Therefore, alongside a tailored business process, the framework was given an additional objective: to produce a matching CMMS implementation specification, that includes all of the necessary functionality required to successfully support the tailored MD process. This approach would deliver yet more innovation – by combining a

business process design tool with a software implementation tool to solve a common industry problem.

- **Submission 5: A Literature-based Preliminary Solution**
  - An initial version of the framework was developed via the synthesis of all existing MD practices that could be found in the literature, via 81 sources from a variety of different industries and sectors. It is presented in detail in Submission 5.

- **Submission 6: Confirmation and Improvement of Initial Framework Design via Expert Elicitation**
  - 12 Industry experts were independently consulted to review the preliminary literature-based framework (from the UK and Australia; covering the Oil & gas, Nuclear, Chemical, Utilities, Power generation, Steel, and Infrastructure sectors).
  - A modified Delphi methodology was utilised to elicit and consolidate their improvement suggestions – consisting of a face-to-face interview (2 hours) and a follow-up survey to clarify any contentious opinions.
  - 176 framework improvements / expansions were identified in total.

- **Submission 7: Presentation of Framework v2**
  - A detailed write-up of the final version of the framework is presented in Submission 7. It was developed by implementing all 176 improvements identified above in Submission 6.
  - The final framework design includes a series of flowcharts covering 157 core process steps, 109 contextual options, and 30,000+ words of guidance.

- **Submission 8: Implementation of Framework in the Sponsor Company and Assessment of Impact on the Defined Problem**
  - The framework was presented to senior management at the sponsor company, and was subsequently adopted as the new global standard for MD. It was then utilised to define a thorough specification of CMMS requirements for each site in the business.
  - A major CMMS improvement project was undertaken, led by the author, to upgrade the MD software functionality at all sites, in order to bring it in line

with the new CMMS specification (produced using the framework). A total of 57 CMMS improvements were implemented.
  - A new MD process was implemented at one of the sponsor's manufacturing sites (i.e. the new facility as described in Submission 1). A thorough example of the tailoring process is documented in Submission 8, with evidence presented to demonstrate the new practices introduced to the business and to validate their positive impact.
  - An assessment was carried out to determine if the original gaps from the Problem Definition had been successfully closed by the implementation of the framework, utilising the same assessment methodology as in Submission 3.
  - The result was overwhelmingly positive, demonstrating a significant improvement in the site's MD processes and systems, sufficient to close all of the high-risk gaps in the sponsor's AMS that were originally identified in Submission 3. The site was subsequently recognised as utilising industry best practice by an independent third party.

Other miscellaneous portfolio submissions include:

- **Innovation Report:**
  - This document, which summarises the entire portfolio with a focus on the research findings and innovations.
- **Personal Profile**:
  - Documents how the various personal competencies required by the EngD programme were met.
  - Describes the 8 taught MSc modules that were undertaken as part of the EngD programme, their resulting marks, and their relevance to the research project.
- **International Placement Report:**
  - It is a requirement of the EngD programme to undertake a 2-week placement (minimum) in a company based internationally. The author chose to work for an AM consultancy firm based in Sydney, Australia. This report details the activities undertaken during the placement, the associated benefits / learning outcomes, and their impact on this research project.

- **Summary of Publications / Conference Presentations:**
    - This document contains details of the publications written and the conference presentations delivered by the author in relation to this EngD (i.e. 1 published journal paper, 1 conference presentation, 1 conference discussion panel).

The remainder of this innovation report will be structured with one section dedicated to each of the submissions described above, with an Innovation Summary at the end in section 10.

1.2. *Scope of Research*

In summary, this research focused on the development of a tailorable framework of practices for MD: i.e. a flexible business process design tool which was developed in order to resolve a series of specific gaps identified in the sponsor company's AMS. The framework was developed by first extracting MD practices from the literature (via a descriptive coding methodology) and then by combining these with practices from industry via elicitation from industry experts (via a Delphi methodology). The scope of the project also included the implementation and testing of the framework in the sponsor company, in order to demonstrate a closure of the gaps originally identified in the problem definition.

2. Project Background

This section will provide a detailed background to the project by introducing the sponsor company and the principal research subject, Asset Management (AM). Note that the sponsor company wishes to remain anonymous throughout this report, therefore only limited details will be provided here.

2.1. *The Sponsor Company*

The sponsor is a large manufacturing company within the nuclear energy sector with a significant market share and a turnover in the billions of pounds. They operate several manufacturing sites across the globe, with customers in many countries. The company is currently constructing a new facility, which is designed to provide treatment and long-term storage of waste nuclear material for public safety and environmental-sustainability reasons. The new facility is very different to its existing asset base, and utilises technology that is outside of the sponsor’s usual area of expertise. Therefore it was anticipated that its existing AM practices would not be suitable for the new plant. The subject area of AM is introduced in the next section.

2.2. *Asset Management*

At the beginning of this research project, in 2014, the discipline of AM was gaining prominence both in academia and industry (Komonen, 2012, O'Hanlon, 2015, El-Akruti and Dwight, 2013) – in particular due to the release of the international standard for AM Systems, ISO 55000, which was publised in the same year (British Standards Institute, 2014a; British Standards Institute, 2014b; British Standards Institute, 2014c). However, according to several sources at the time, the discipline was still in the early stages of development and there was no single, widely-recognised definition (Van der Lei, 2012, Kennedy, 2013, El-Akruti and Dwight, 2013). There were a number of national and international organisations that each presented their own (slightly different) definitions of AM – e.g. the AM Council of Australia, the Institute of AM UK, the European Research Network on Strategic Engineering AM – therefore several definitions were reviewed from a variety of sources (British Standards Institute, 2008a; Hastings, 2010; Komonen, 2012) and the following observations were derived:

1. All definitions concerned ***physical*** or ***engineering assets***. This refers to assets not in the financial sense (the typical historical use of the term (Liyanage, 2012)), but as physical items that generate value for an organisation via the delivery of products or services (Liyanage, 2012, McGlynn and Knowlton, 2011, El-Akruti and Dwight, 2013, British Standards Institute, 2008a). Physical assets can include buildings, manufacturing plants, infrastructure, mobile assets, and information technology (Liyanage, 2012, Barry, 2011, Hastings, 2010).
2. They concern the ***management*** of those assets: i.e. applying sound judgement and decision making, both technical and financial, to determine which assets are needed and how to sustain them (Hastings, 2010). Komonen (2012) describes how AM is becoming an essential management activity.
3. AM takes place over the ***entire life-cycle*** of the asset, from creation to disposal. Several authors present the asset life-cycle stages in subtly different ways, but the following amalgamation will be used to suit the purposes of this research: concept, design, construction, commissioning, operations, maintenance, modification and disposal (Van der Lei, 2012, Barry, 2011, British Standards Institute, 2002, British Standards Institute, 2008a).
4. Assets are managed in order to ***achieve business objectives***. As an alternative, this is sometimes described as ***realising value*** (British Standards Institute, 2014a). The reason a business invests in an asset is for it to contribute towards the delivery of the business's objectives. If it doesn't achieve this then the asset doesn't return any value for the business – i.e. it is a wasted investment. Or put another way: the output generated by an asset should justify its ownership (El-Akruti and Dwight, 2013).

In summary, AM can be defined as:

> **"*The management of physical assets over their entire life-cycle in order to achieve business objectives".***

2.2.1. ISO 55000

However, ISO 55000, which as described above was published in 2014 and aimed to represent an international consensus on the subject, also attempts to provide a standard definition for AM, i.e.:

> ***"coordinated activity of an organisation to realise value from assets"*** (British Standards Institute, 2014a)***.***

However, a number of criticisms can be made regarding this definition. Firstly, the ISO standard deliberately omits the term "physical" from its definition, in order to allow the principles of AM to apply to any type of asset, tangible or intangible (Ma, Zhou, and Sheng, 2014, Hodkiewicz, 2015). Whilst this is a worthwhile attempt to reach a wider audience, it actually makes the definition much too broad, diluting the meaning of the subject and distancing it from its original intent. AM originally branched out from the maintenance community in the early 1990's in Australia and the UK (Kennedy, 2015; Institute of Asset Management, 2018a). The vast majority of AM practitioners are focused entirely on physical assets: AM conferences and seminars are generally targeted at a maintenance audience (DFA Media, 2016, Institution of Mechanical Engineers, 2016), and many maintenance societies and institutions also cover the discipline of AM (The Irish Maintenance and Asset Management Society, 2014, Global Forum on Maintenance and Asset Management, 2016; European Federation of National Maintenance Societies, 2018). By excluding the term "physical" from the definition, the ISO standard ignores the reality of how AM is practiced in the real world. In either case, for the purposes of this research the "physical" aspect will very much apply, because as will be seen later in section 5, the research subject will be adjusted to focus entirely on the delivery of maintenance.

A second criticism of the ISO definition is its omission of the phrase "entire life-cycle". The original intent of the subject of AM was to introduce a new way of thinking for senior management at asset-intensive organisations, i.e. one of long term, whole life-cycle thinking (Kennedy, 2015). This "whole life-cycle" approach is regarded by several authors as the most significant new thinking introduced by the discipline (Van der Lei, 2012, Wilson, 2013a, El-Akruti and Dwight, 2013). As shown below in Fig. 2, the asset life-cycle stages defined earlier (see section 2.2, point 3) can be grouped into two broader phases (Blanchard and Fabrycky, 1998): the earlier half known as "acquisition" (i.e. from concept to commissioning) and the latter half known as "utilisation" (i.e. from operations to disposal). Note that some authors group operations, maintenance and modification together into one phase because they generally follow each other in a cyclic pattern throughout an asset's operational life (Campbell and Reyes-Picknell, 2006; British Standards Institute, 2015a).

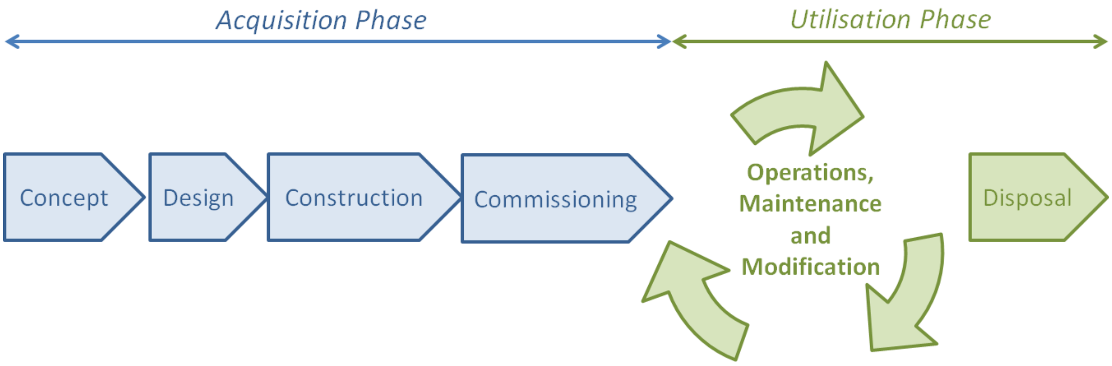


Fig. 2 – The Acquisition and Utilisation asset life-cycle phases, adapted from (Blanchard and Fabrycky, 1998; Campbell and Reyes-Picknell, 2006; British Standards Institute, 2015a).

In industry these two broader phases have traditionally been managed separately (Van der Lei, 2012, Liyanage, 2012), with a project team creating the asset and then handing over the finished article to an operator. But with AM thinking this approach is now regarded as flawed (Van der Lei, 2012; Kennedy, 2015). For asset-intensive industries, it is the utilisation phase that represents the greatest portion of total life-cycle cost – operations and maintenance costs often outweigh the initial capital investment (Parida, 2012, McGlynn and Knowlton, 2011, Wilson, 2013b). However, it is the acquisition phase that has the most influence on the ability to control these costs during utilisation (British Standards Institute, 2004; Campbell and Reyes-Picknell, 2006, Davis and Wilson, 2013, El-Akruti and Dwight, 2013); asset operating costs can be fixed by up to as much as 65% according to Barringer (1997) and up to 70% according to Davis and Wilson (2013) due to the reliability inherent in the design. Several authors argue that there should be greater interaction between these two phases, with operations and maintenance professionals involved in the decisions made during design to ensure greater asset maintainability (Campbell and Reyes-Picknell, 2006, Davis and Wilson, 2013). Without this inter-life-cycle approach, potential benefits to maintainability are missed in the design phase due to the short-term thinking of project teams, who are often only focused on the acquisition of assets as quickly and cheaply as possible (El-Akruti and Dwight, 2013; Kennedy, 2015). By omitting the "life-cycle" component from its definition of AM, the ISO standard ignores arguably the most important aspect of the subject.

Note that whilst some AM organisations have adopted the ISO 55000 definition since its release (Institute of Asset Management, 2014), other prominent institutions have quite notably kept their original definitions intact (Asset Management Council, 2018), potentially due to the same criticisms that the author has raised above. The Global Forum on

Maintenance and Asset Management, an organisation which aims to provide businesses with guidance on how to align with ISO 55000, also utilises the ISO definition in its principle publication *The Asset Management Landscape* (Global Forum on Maintenance and Asset Management, 2014). But curiously, immediately below the definition it then provides a paragraph offering further clarification, where it explains concepts such as physical assets and the importance of whole life-cycle thinking. One would think that if the definition was sufficient in its own right then this further clarification would not be necessary.

2.2.2. The Asset Management System

In order to deliver effective AM, most AM institutions advocate the development and implementation of an Asset Management System (AMS) (British Standards Institute, 2014a; Asset Management Council, 2017; Institute of Asset Management, 2018b). An AMS can be defined as a "management system for asset management": i.e. a set of organisational policies and procedures for AM, with clearly defined objectives and business processes that enable those objectives to be achieved (British Standards Institute, 2014a). It is essentially a system which defines what an organisation needs to achieve in terms of AM, and then outlines the processes and systems that it must implement in order to achieve those objectives (El-Akruti and Dwight, 2013).

2.3. *Initial Problem Definition*

Therefore – returning to the issue raised in section 2.1 – because the sponsor of this research needed to deliver effective AM at its new facility, the best route to this would be to ensure that it had a suitable AMS, so that effective AM processes and systems would be developed and implemented.

It was recognised that in order to develop an effective AMS it would be necessary to utilise a requirements framework (RF): i.e. a guidance document that clearly defines the essential content and structure of an AMS (Kennedy, 2013). The sponsor suggested the use of a specific AMS RF – i.e. the ISO 55000 standard, which as discussed earlier had recently been published (British Standards Institute, 2014a). Like all ISO standards, ISO 55000 was developed internationally by a collaboration of organisations and aimed to represent a worldwide consensus (The International Organization for Standardization, 2015). Because of this, the sponsor believed that alignment with ISO 55000 would result in the most effective AMS possible, and deliver the greatest AM performance. However, the author recognised that this was purely an assumption, and that several alternative AMS RFs existed that could potentially be more suitable for the sponsor company (El-Akruti and Dwight, 2013). Therefore an objective was set to test the sponsor's assumption – ISO 55000 would be critically reviewed and compared to all available alternatives in order to reach an objective conclusion.

2.3.1. Initial Research Question

An initial Research Question was defined at this stage to provide a focus for the early phases of the project. It was specifically related to developing an AMS for the sponsor's new site in alignment with ISO 55000:

> ***How can [the sponsor company] develop and implement an Asset Management System for [its new facility] that fully complies with all requirements of the ISO 55000 standard?***

This Research Question relied on 2 assumptions:

1. That ISO 55000 would be proven to be the most suitable framework on which to develop the sponsor's new AMS.
2. That developing an AMS for the sponsor's new site would be a feasible research aim, which would involve filling several moderate gaps in the sponsor's existing AMS.

These assumptions were later tested in order to validate the Research Question (a process that is documented in detail in sections 3 and 4 of this report). In summary, whilst assumption 1 was proven to be valid (see section 3), assumption 2 was found to be untenable due to the huge scale of the gaps identified in the sponsor's existing AMS that was in use at its other sites (see section 4). Therefore, the initial Research Question was consequently revised in order to focus on the most significant gaps, as discussed in section 5 of this report.

3. An Assessment of ISO 55000 and its Alternatives

An assessment was carried out to test the first assumption that was made above in section 2.3.1, i.e. that ISO 55000 was the most suitable AMS RF available on which to develop the sponsor's new AMS. The ISO standard was compared to all available alternatives in order to reach an objective conclusion.

3.1. *Methodology*

The methodology for assessing ISO 55000 consisted of two broad parts:

1. The identification of alternatives to ISO 55000 (i.e. other AMS RFs).
2. The evaluation of ISO 55000 and its alternatives to determine their completeness.

The aim was to identify every possible AMS RF available in the literature and assess them all in order to determine which framework was the most comprehensive – i.e. which one had the fewest gaps in terms of AMS requirements. The framework with the fewest gaps will in turn produce an AMS that has fewer gaps, and is therefore more likely to be effective.

3.1.1. The Identification of Alternatives to ISO 55000

For something to be considered a viable alternative to ISO 55000 it had to define a framework of requirements for an AMS and meet the following acceptance criteria:

Criteria 1. It must use an AMS definition that is compatible with this research, i.e. a set of documented processes and systems that an organisation must implement in order to achieve its AM objectives (see section 2.2.2). In some cases, the term "Asset Management System" was found to be incorrectly used to describe a software package for managing asset data and for facilitating the planning and control of maintenance activities (Amadi-Echendu et al., 2010, Too, 2010, Institute of Asset Management, 2014, Ma, Zhou, and Sheng, 2014). This type of "AMS", should actually be referred to as a Computerised Maintenance Management System (CMMS); therefore any sources that described such systems were not compatible with this research and were dismissed.

Example – Designing an improving asset management system for offshore drilling operations (Riddell, 2008). Based on its title, this paper appears to be describing an AMS, but in actual fact it defines the core components of a CMMS. It is using the term "AMS" incorrectly, evidenced by its stated requirements, which include internet connectivity, a secure central database, and software reliability. It is clear that the author is referring to a software package for managing asset data, not a series of documented processes and systems for achieving AM objectives – therefore this paper does not meet Criteria 1.

Criteria 2. It must not be a detailed guidance document explaining *how* to implement the specific practices and processes that make up an AMS; it must outline only the *requirements and structure* of an AMS (i.e. the "what" to do, not the "how" to do it (British Standards Institute, 2008a, Department for Transport, 2013)). Documents that provided both requirements and guidance were still reviewed if the requirements were unique (i.e. they were not based on ISO 55000 or its predecessor PAS 55, which were already in scope for review). Documents that were purely guidance were rejected.

Example – Life-cycle Engineering's Asset Management System Framework: Using Asset Management Capabilities to Create Value (Life-cycle Engineering, 2014). This article provides guidance on how to implement some of the AM processes that are specified as requirements in ISO 55001. For example, a Work Management Process is defined in detail, which is intended to fulfil the requirements of ISO 55001 clause 8.1 – Operational planning and control (British Standards Institute, 2014b). The guidance contained in this article is not suitable for review, and the requirements are taken directly from ISO 55001, which was already in scope for review; therefore this article did not meet Criteria 2.

Criteria 3. It was anticipated that some search results would return an AMS, rather than a RF for an AMS. In some cases it may have been possible to analyse such an AMS and "work backwards" to determine the requirements that must have been utilised to develop it, based on its content. However, if it was clear that the source requirements came directly from ISO 55000 (or its predecessor PAS 55), then they were rejected because these RFs were already in scope for review.

Example – Network Rail Asset Management Strategy (Network Rail, 2014). This document forms part of Network Rail's AMS. It is their AM strategy document – written in order to comply with clause 6 of ISO 55000. However, this document does not meet Criteria 3, because it clearly states that the RF that was used to develop it was ISO 55000, which was already in scope for review.

An exhaustive literature search was carried out to identify as many alternative AMS RFs as possible, in accordance with the acceptance criteria defined above. A variety of sources were utilised, including the various database subscriptions available to University of Warwick students (e.g. ProQuest, Emerald Insight and OECD iLibrary) and the websites of the following national and international AM societies and institutions:

- IAM (The Institute of AM, UK)
- The AM Council of Australia
- The Asset Institute (Australia)
- EURENSEAM (The European Research Network for Strategic Engineering Asset Management)
- ISEAM (International Society of Engineering Asset Management)
- GFMAM (Global Forum on Maintenance and Asset Management)
- ABRAMAN (Brazilian Maintenance Association)
- IFRAMI (French Institute of Asset Management and Infrastructure)
- EFNMS (European Federation of National Maintenance Societies)
- FIM (South American Maintenance Society)
- GSMP (Gulf Society of Maintenance Professionals)
- SMRP (Society for Maintenance and Reliability Professionals, USA)
- JIPM (Japan Institute of Plant Maintenance)
- PEMAC (Plant Engineering and Maintenance Association of Canada)
- SAAMA (South African Asset Management Association)

Note that any material from these AM institutions that was considered detailed AMS guidance (i.e. material that did not meet acceptance criteria 2), or any material not readily available in the English language, was not accepted.

3.1.2. The evaluation of ISO 55000 and its alternatives

A descriptive coding method (Saldaña, 2011; 2014) was utilised to concisely summarise the content of each AMS RF. Each AMS requirement that was identified was assigned a unique code, which was then compiled into a codebook with a clear description to define its meaning (Tracy, 2013). The same codes were used throughout the analysis and across all RFs, enabling a fair comparison of content to be made in order to determine which RF was the most comprehensive.

In order to facilitate the analysis process, and the eventual comparison of RFs, the codebook was structured using a second level of coding. This second level utilised the hierarchical coding method, also known as the axial method (Tracy, 2013, Yin, 2015), to group the codes into categories. 3 layers of hierarchy were utilised to achieve sufficient categorisation: the first representing the top-level AMS *sections* (e.g. Strategy, Leadership, Evaluation); the second representing core AMS *components or processes* (e.g. the process for performance measurement, the process for risk management); the third and lowest level represented the detailed *requirements* of each component or process (e.g. performance measurement shall consider the requirements of key stakeholders).

The codebook was developed gradually as the analysis was carried out. The first RF was analysed to build up an initial list of codes summarising its entire content. These codes were then used to analyse the 2nd RF in order to compare its content with the first. As new codes were identified (i.e. requirements that were not present in the first RF), they were added to the codebook. This process was repeated until all RFs had been analysed, and the codebook contained a complete list of all possible codes from all available RFs. The finished codebook therefore contained a combination of all possible AMS requirements that existed in the literature. A results table was constructed to show the complete list of codes against all available RFs (see Table 2 for an extract or Appendix A for the complete codebook), highlighting where codes were present or absent to allow a comparison of content to be made. It was then possible to conclude that the RF with the fewest gaps was the most comprehensive available in the literature.

3.1.3. Limitations

It was recognised that the most comprehensive RF (i.e. the one with the fewest missing codes) may not necessarily be the best choice for the sponsor. Some codes are arguably more important than others, but the methodology did not account for this; it would be more credible to apply an importance weighting to each code and factor this into the analysis. However, the importance of any given AMS requirement is difficult to quantify because it generally depends on the context – i.e. each organisation will put more emphasis on different sections of their AMS, depending on the nature of their business. Therefore the development of such a set of importance weightings for the sponsor would be a highly subjective process, and if the author were to carry out this exercise alone, the result would be of little credibility. Only by consulting a range of experts with detailed knowledge of both the subject of AM and the business context of the sponsor, could a credible set of weightings be developed. However, such a range of experts did not exist within the sponsor company, and for those few that did exist, their time was not available for use in this research project. Therefore the only feasible option was to perform the analysis as described above in section 3.1.2, without a weighting element, and then address this limitation via further analysis. This further analysis consisted of the following method: the RF which had the fewest code gaps was not immediately treated as the most suitable for the sponsor, but was subjected to further assessment by analysing each of its gaps in detail to determine their significance in the sponsor's context (i.e. was their absence allowable?).

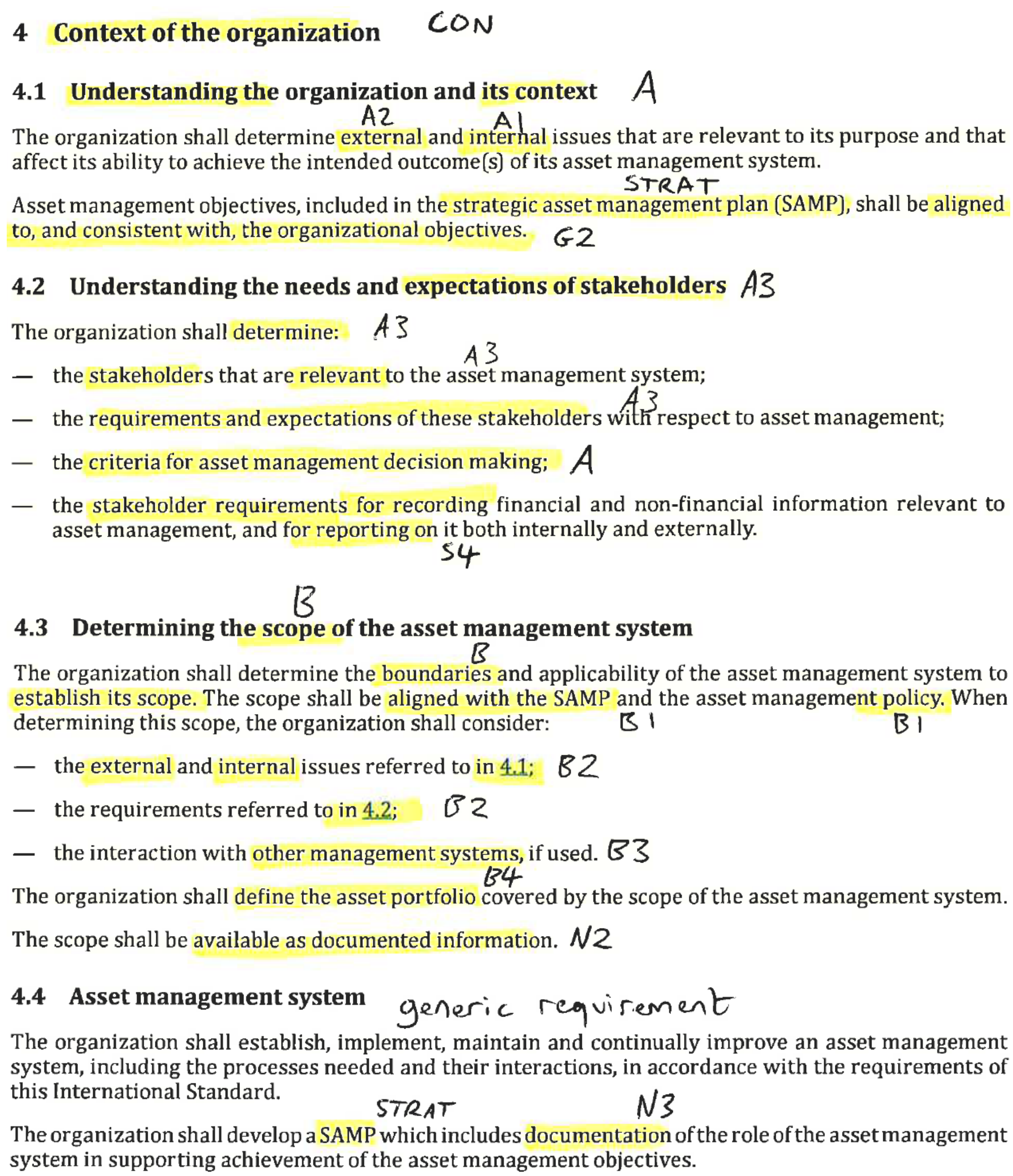
Another potential limitation of the methodology described above was that the first RF to be analysed would always have a greater influence over the terminology used in the code descriptions, and over the structure and layout of the codebook, potentially leading to a biased outcome. However, this actually had a positive effect in this case, because ISO 55000 was analysed first. Recall that the purpose of this exercise was to compare ISO 55000 against its alternatives to determine which was the most comprehensive. Therefore by analysing ISO 55000 first, this caused the end results table to be worded and structured according to the ISO terminology and format, which actually allowed any deviations present in the other RFs to be more easily identified (whether positive or negative). This made it easier to analyse the results and draw useful conclusions.

Another limitation with the methodology was that mistakes could have been made during the analysis due to human error. There was a potential for meaningful content to be overlooked or misinterpreted, or for additional codes to be allocated where the meaning was not actually present in the text. This would have led to inaccurate results, potentially giving the false impression that a particular RF was more / less comprehensive than it was in reality. To counter this concern, each RF was read through in full before it was coded, to ensure that the content and context was properly understood. This was essential for allocating the correct codes in order to capture the true meaning of the text.

Another potential issue was the possibility of repeated content within RFs; it was important that this was recognised and not double-counted with a new code. This would have caused two codes to be created which in reality had the same meaning, which would have effectively given that content double the importance. Any RFs that did not contain that content would have been missing two codes from the results table instead of one, making them appear less comprehensive than they really were. To avoid double coding, multiple passes were made through each document to check for consistency and to ensure a thorough and logical code allocation. The precise number of passes depended on the complexity of the document; essentially the analysis was repeated indefinitely in each case until a complete pass was made where no new codes or errors were found.

3.1.4. Coding Process Example – The First Clause of ISO 55001

An example is given below to demonstrate the coding process that was be used; Fig. 3 shows the coding of the first clause of ISO 55001 (i.e. clause 4. Note that clauses 1 -3 contain the document scope, normative reference and terms and definitions, and were therefore excluded from the analysis because they do not define any AMS requirements).



4 Context of the organization

4.1 Understanding the organization and its context

The organization shall determine external and internal issues that are relevant to its purpose and that affect its ability to achieve the intended outcome(s) of its asset management system.

Asset management objectives, included in the strategic asset management plan (SAMP), shall be aligned to, and consistent with, the organizational objectives.

4.2 Understanding the needs and expectations of stakeholders

The organization shall determine:

— the stakeholders that are relevant to the asset management system;

— the requirements and expectations of these stakeholders with respect to asset management;

— the criteria for asset management decision making;

— the stakeholder requirements for recording financial and non-financial information relevant to asset management, and for reporting on it both internally and externally.

4.3 Determining the scope of the asset management system

The organization shall determine the boundaries and applicability of the asset management system to establish its scope. The scope shall be aligned with the SAMP and the asset management policy. When determining this scope, the organization shall consider:

— the external and internal issues referred to in 4.1;

— the requirements referred to in 4.2;

— the interaction with other management systems, if used.

The organization shall define the asset portfolio covered by the scope of the asset management system.

The scope shall be available as documented information.

4.4 Asset management system

The organization shall establish, implement, maintain and continually improve an asset management system, including the processes needed and their interactions, in accordance with the requirements of this International Standard.

The organization shall develop a SAMP which includes documentation of the role of the asset management system in supporting achievement of the asset management objectives.

Fig. 3 – Example of the coding process using ISO 55001 (British Standards Institute, 2014b)

Observe that key meanings have been highlighted and assigned a unique code, which is structured according to its position in the code hierarchy: *sections* are assigned a short abbreviation (e.g. CON), *components* or *processes* are assigned a single letter (e.g. A), and *requirements* within that component or process are assigned the same letter followed by a number (e.g. A1).

Table 1 below demonstrates the process of compiling these codes and code descriptions into the codebook (codes are shown in brackets to the left of code descriptions). Note that the table shows the *final* code allocations for clause 4, which were only determined after multiple passes of the entire document; there are codes present in clause 4 which are in fact repetitions or references to other clauses found later in the document. Any codes which are highlighted in red are those which were not actually present in clause 4, but have been added for information purposes.

Section	***Component or Process***	***Requirement***
(CON) Organisational Context	**(A)** Determine the organisational context and how this should impact AM decisions	**(A1)** Consider the internal context
		(A2) Consider the external context
		(A3) Consider stakeholder's needs and expectations
	(B) Determine the scope of the AMS	**(B1)** The scope must align with the AM policy (Component D) and strategy (Section STRAT)
		(B2) The scope must align with the organisational context (Component A)
		(B3) The scope must align with other company Management Systems
		(B4) The scope must define the asset portfolio covered by the AMS
(STRAT) Asset Management Strategy	**(G)** Develop a process for setting AM objectives	**(G2)** AM objectives must align with the wider organisational objectives
(SUPP) Support	**(N)** Determine AM Documentation Requirements	**(N2)** The AMS shall include an "AMS Scope" document which describes the outcome of Component B (AMS Scope)
		(N3) The AMS shall include an "AM Strategy" document which describes Components F (AM Risk Management process), G (AM Objective setting process) and H (process for developing AM Plans) and the details the outcome of process G (the AM objectives)
(EVAL) Evaluation	**(S)** Develop processes for Performance Measurement and Reporting	**(S4)** Consider any measures required by key stakeholders, both internally or externally

Table 1 – Example of the ISO 55001 clause 4 codes being compiled into the codebook

The allocated code structure and all descriptions shown in Table 1 are the author's attempt to summarise the meaning of the original text in a concise manner. One limitation of this method is that it relies on one individual's interpretation, which is of course subjective; the end result could vary depending on who carried out the analysis, and this potential variation could give less credibility to any conclusions drawn from the end result. One potential solution to counter this limitation would be to utilise a second independent person to check the work and possibly provide more confidence to the analysis – however, since coding is a highly interpretive methodology, a second analysis from a different person would likely result in very different codes (Saldana, 2009), which would not serve to increase confidence anyway. Regardless, this is a solo EngD project, and such a secondary resource was not available, especially when taking into consideration the large volume of documents to re-analyse and code.

As an alternative to a second independent analysis, a selection of the decisions made in the example above (Fig. 3 and Table 1) will be explained below to justify the author's method of interpretation:

Regarding the highest-level *Section* codes:

- Clause 4 of ISO 55001 was assigned its own *section* of the codebook **(CON)**, which contains all codes relevant to "Organisational Context".

Regarding the 2nd tier *Component* or *Process* codes:

- The CON *section* was broken down into 2 *components*, coded A and B:
    - **(A)** Determine the organisational context and how this should impact AM decisions
    - **(B)** Determine the scope of the AMS

  As can be seen in Fig.3, this structure is different to clause 4 of ISO 55001, which is broken down into 4 parts rather than 2. However, it could be argued that clause 4.2 is really an extension of 4.1: both are asking the reader to consider people and issues that form the context of the organisation and influence the way it makes decisions; therefore both clauses have been combined to form *component* A in the codebook. Clause 4.3 covers a distinguishably different requirement, i.e. the AMS scope; therefore this is given its own *component* designation in the codebook (i.e. B). However, clause 4.4 contains very little meaning that is not already repeated elsewhere in the standard; the requirement for an AMS is entirely generic, as this is the implicit purpose of ISO 55001 anyway, and therefore does not require its own code.

Regarding the 3rd tier *Requirements* codes:

- Firstly consider clause 4.1:
    - Internal and external issues are clear, discrete requirements to take into consideration when determining the organisational context, therefore they are allocated their own codes, A1 and A2.
    - The requirement to develop a strategic AM plan (SAMP) is repeated several times throughout the ISO 55001 standard; it is not unique to clause 4.1. The requirement actually has its own clause (i.e. clause 6), which details the SAMP content and requirements in detail – therefore the presence of this requirement is clause 4.1 is really just for reference (because the output of this clause – i.e. an understanding of the organisational context – is an input to the SAMP). To give it a new code here (e.g. A4) would actually be double-coding (as described earlier – section 3.1.3) because the content is already coded in clause 6. This is a good example of the need to thoroughly read and understand the entire text before starting the code allocation process, to avoid double coding.
    - The requirement for the SAMP to be aligned with the organisational objectives is assigned the code G2; this is an example of a hidden reference to a later clause (i.e. clause 6.2.1 – AM Objectives), which is only recognisable after making multiple passes through the document (as described earlier in section 3.1.3).

- Regarding clause 4.2:
    - As described earlier, this clause can be viewed as an extension of clause 4.1 as it is still related to the organisational context, but specific to the stakeholder's influence on that context. The next 3 statements under clause 4.2 are all stating different elements of the same requirement: i.e. that all relevant stakeholders need to be identified and their needs and expectations need to be captured to determine how this impacts the context of the organisation and the way it makes decisions. This is summarised more concisely by the code (A3) and its description: *identify and consider relevant stakeholder's needs and*

expectations. Note that the second half of this requirement (i.e. "and how this impacts the context of the organisation and the way it makes decisions") is already included in the description for code A, which is directly above code A3 in the codebook hierarchy and therefore does not need to be repeated. This demonstrates the benefits of a hierarchical coding structure.

- The requirement to consider "the criteria for asset management decision making" is not just relevant to stakeholders (i.e. clause 4.2); this requirement actually captures the overall purpose of Component A (i.e. clause 4.1 and 4.2). This is only revealed by reading other clauses in the standard, particularly clause 6, which shows that the reason for determining the organisational context is to use it as an input for making AM-related decisions (e.g. in the risk management and objective setting processes). Therefore since the "decision-making criteria" requirement is integral to all of Component A, it is incorporated into its description.
- The requirement to consider stakeholder's performance measurement and reporting needs is another example of a code that is better placed in a later section of the codebook (i.e. code S4), as it strongly relates to a later clause on measurement and reporting (i.e. clause 9.1).

3.2. *Results*

38 potential AMS RFs were identified in the literature, and 12 of these met the acceptance criteria that were defined earlier in section 3.1.1 (a table presenting a list of all 38 items, complete with reasons for acceptance / rejection, can be found in Appendix B). Each of the 12 accepted frameworks were analysed according to the methodology described in section 3.1.2, as demonstrated in the example in section 3.1.4.

A results table was compiled showing the complete list of codes that resulted from this analysis (i.e. the codebook), cross-referenced against all accepted AMS RFs; Table 2, beginning on the next page, shows an extract from this results table (see Appendix A for the entire codebook). An "x" is used to indicate where the codes were present in each of the AMS RFs that were reviewed. Note that the last row of the results table, showing the final "% complete" score for each framework, has also been included in Table 2.

Section	Section Description	AMS Core Components (letter) & their Requirements (number)			ISO 55001 (British Standards Institute, 2014b)	PAS 55-1 (British Standards Institute, 2008a)	(Department of Local Government, 2011)	(El-Akruti and Dwight, 2013)	(Water Environment Research Foundation, 2005)	(Asset Management Council, 2014)	(US Department of Transportation, 2007)	(Washington State Department of Health, 2009)	(OECD, 2001)	(Crist, et al., 2013)	(Younis and Knight, 2012)	(Brown et al., 2012)
CON	**Organisational Context**	**A**	**Determine the organisational context and how this should impact AM decisions**		**x**	**x**			**x**	**x**			**x**	**x**		**x**
			A1	Consider the internal context	x		x	x	x	x			x		x	
			A2	Consider the external context	x			x	x							x
			A3	Identify and consider relevant stakeholder's needs and expectations	x	x	x		x	x	x	x	x	x	x	x
		B	**Determine the scope of the AMS**		**x**	**x**	**x**			**x**						
			B1	The scope must align with the AM policy (Component D) and strategy (Section STRAT)	x											
			B2	The scope must align with the organisational context (Component A)	x					x						
			B3	The scope must align with other company Management Systems	x					x						
			B4	The scope must define the asset portfolio covered by the AMS	x				x	x	x	x		x		x
LEAD	**Leadership**	**C**	**Leaders must show commitment to the AMS**		**x**	**x**	**x**			**x**						**x**
			C1	Ensure all AMS requirements are implemented in full	x	x	x									
			C2	Ensure sufficient resources are available to fulfil the requirements of the AMS	x	x	x									
			C3	Ensure there is sufficient cross-functional collaboration to enable effective AM	x											x
			C4	Ensure the required AM performance is achieved and continually improved	x	x										
			C5	Ensure others are sufficiently directed, supported and authorised to be able to contribute effectively to AM performance	x	x	x			x						
			C6	Ensure AMS processes align with and are compatible with other organisational processes	x	x		x								
			C7	Appoint a member of top management who shall have overall responsibility for the development of the AMS		x	x									
			C8	If a change of culture is required to achieve AM performance, ensure that this is led from the top of the organisation	x	x			x		x					x
		D	**Define an AM Policy**		**x**	**x**	**x**	**x**		**x**	**x**		**x**	**x**		**x**
			D1	AM Policy must align to the wider organisational purpose, vision and strategy	x	x					x			x		x
			D2	AM Policy must be consistent with other relevant organisational policies and processes	x	x										x
			D3	Policy must include a commitment to the delivery and continual improvement of AM performance	x	x										
		E	**Define AM Roles & Responsibilities**		**x**	**x**	**x**			**x**				**x**		
			E1	Ensure that all roles necessary to deliver the AMS requirements are assigned	x	x										x
STRAT	**AM Strategy**	**F**	**Develop a Risk Management process for AM**		**x**	**x**			**x**	**x**	**x**					**x**
			F1	Align AM risk management with the wider organisational risk management process	x	x				x	x					
			F2	Identify any risks or opportunities that could have an impact on AM performance	x	x					x			x		x
			F3	Consider the organisational context (Component A) when identifying AM risks	x	x				x	x					
			F4	Ensure that these risks are managed as part of the AM Strategy, i.e. risks are fed into the AM objective setting process (Component G) and subsequently plans are put in place to address them (Component H)	x	x				x	x					
			F5	Ensure that emergency situations and contingency planning are considered	x											
[130 codes in total across 24 core AMS components]																
				Number of codes missing:	**14**	**16**	**97**	**112**	**110**	**89**	**106**	**119**	**115**	**106**	**113**	**93**
				% Complete:	*89*	*88*	*25*	*14*	*15*	*32*	*18*	*8*	*12*	*18*	*13*	*28*

Table 2 – Extract of results table showing code allocations against accepted AMS RFs

3.3. *Analysis*

The second-to-last row in Table 2 shows the *number of codes missing* from each AMS RF, when compared to the combined list of codes from all RFs available in the literature. Observe that:

- ISO 55001 has the fewest gaps (i.e. 14 gaps)
- PAS 55 has the second fewest (i.e. 16 gaps)
- The AM Council's Framework for AM has the third fewest (i.e. 89 gaps)

Because ISO 55001 and PAS 55 led by a significant margin, it was considered reasonable to discount all other RFs at this stage – because they all had a significant amount of missing content, which would have caused any AMS based upon them to contain significant gaps, which would in turn have led to poor AM performance. However, because the difference between the two leading RFs was so narrow, it was not considered reasonable to draw a conclusion as to which of them was the most suitable for the sponsor without further analysis. As discussed in section 3.1.3, some codes may have been more significant than others in the sponsor's context, therefore a judgement could not have been made without first assessing the significance of the missing codes from each of the two leading frameworks.

3.3.1. Hypothesis – ISO 55001 is the most suitable framework

It was observed that all of the 14 codes missing from ISO 55001 were present in PAS 55, and all of the 16 codes missing from PAS 55 were present in ISO 55001 (see Appendix A). Interestingly, ISO 55000 is the successor to PAS 55, and when ISO 55000 was developed the authors used the PAS 55 content as a base for the new ISO standard (British Standards Institute, 2015b, O'Hanlon, 2015). Therefore, during the development of ISO 55001, the 14 missing codes must have been delberately removed from the original PAS 55 content, and the 16 extra codes must have been deliberately added. However, it would be wrong to assume that these changes automatically bring improvement in every context: according to Hodkiewicz (2015), the PAS was intended for physical assets only whereas ISO 55000 has been written to apply to any type of asset (e.g. financial, human, intangible assets) (Ma, Zhou, and Sheng, 2014, Hodkiewicz, 2015). Although this change largely just means that the language has been generalised so that it can apply to a wider range of sectors and asset contexts (Ma, Zhou, and Sheng, 2014), it is possible that some of the content which is important for physical assets, such as the sponsor's new manufacturing facility, could have been removed. If so, then the older PAS framework could actually be the more suitable choice.

Further analysis was therefore be undertaken to allow a firm conclusion to be drawn. To facilitate this analysis, a hypothesis was made that ISO 55001 was the more suitable framework – on the basis that the ISO standard was the more recent RF, and because it had officially superceded the PAS (British Standards Institute, 2015b, O'Hanlon, 2015). This hypothesis was tested in the sponsor's context by analysing:

- The 14 gaps in ISO 55001 (when compared to PAS 55) to determine if their absence would be detrimental for physical assets, such as the sponsor's new facility.
- The 16 additions to ISO 55001 (when compared to PAS 55) to determine if these requirements would have a positive or negative impact in the sponsor's context.

3.4. *Conclusion*

This further analysis, carried out as described above in section 3.3.1, revealed that the majority of the content missing from ISO 55001 was actually present in the guidance document, ISO 55002. Therefore, provided that the reader considers the ISO 55000 series in its entirety (i.e. both the requirements in ISO 55001 and the guidance in ISO 55002), it contains almost all of the AMS requirements that exist in the literature, with the following exceptions:

- Appoint a member of top management who shall have responsibility for the development of the AMS (Code C7)
- Develop a Contingency Planning Process (Code FX)
- Document an overview of the main components of the AMS, showing how they interact (Code N5)

When analysed in detail, these requirements were found to be either not applicable in the sponsor's context, or they were already sufficiently covered elsewhere by other clauses in ISO 55001 (see Appendix A).

Additionally, after analysing each piece of "new" content present in the ISO standard when compared to its predecessor PAS 55 (see section 4.3), nothing was found to be detrimental in the sponsor's context. Each of the new requirements were found to be useful additions to the framework that would have a positive impact.

Therefore a conclusion was drawn that ISO 55000 fully covered all applicable AMS requirements available in the literature, and it was the most suitable choice of framework on which to develop the sponsor's AMS.

3.4.1. Innovations

The codebook developed in this chapter (see the extract in Table 2 or the full codebook in Appendix A), is a useful assessment tool for determining if an AMS meets the requirements of ISO 55001 (or any other AMS RF that was reviewed, if so desired). It presents the requirements of the ISO standard in a concise manner with a very clear structure, enabling the end user to assess or develop an AMS much more easily than they could if utilising the source document (which is poorly structured with a great deal of repetition and internal cross referencing, as discovered during the coding process). Because such an assessment tool does not already exist, and because it was demonstrably useful for the sponsor (and potentially for other organisations) in the development of their AMS, it will be claimed as innovative.

Another innovation delivered in this chapter is the methodology itself – i.e. the hierarchical descriptive coding of a standard in order to interpret, simplify and clearly present its requirements in a structured and concise list. This method could be utilised for any other requirements framework (for example other ISO standards) outside of the AM subject area, and could therefore have value in other disciplines such as Quality Management, Health and Safety Management, and Risk Management etc.

4. An Assessment of the Sponsor's Existing Asset Management System

In the previous section, after analysing all available AMS requirements frameworks available in the literature, it was concluded that ISO 55000 (British Standards Institute, 2014a) was the best available framework on which to develop a new AMS for the sponsor's new facility. However, rather than developing an entirely new AMS from scratch, it was assumed (as discussed earlier in section 2.3.1 – see assumption 2) that the sponsor's existing AMS could be largely adopted at the new site, so long as it could be proven to adequately meet the requirements of ISO 55000. Any gaps that did not quite meet the ISO requirements could be addressed by further research as part of this project. Therefore, an assessment was carried out to evaluate the sponsor's existing AMS against ISO 55000, to identify those areas that were adequate and to identify any gaps that would require further development.

4.1. *Methodology*

The assessment was carried out in two stages:

1. A documentation-based review – i.e. an assessment of the sponsor's existing AMS documentation, to determine its completeness against the ISO 55000 requirements.
2. A practices-based review – i.e. an assessment of the observable processes, procedures and systems implemented in the sponsor's existing facilities.

The aim of this approach was to evaluate both the completeness of the formal documentation that was in place for AM, and to assess the standard to which they were implemented on site. It was necessary to do both, because even if the ISO 55000 requirements were adequately "met" in the sponsor's written procedures, this would not guarantee that corresponding processes and/or systems were adequately implemented on site. A true representation of the sponsor's AMS – and its gaps – could only be determined by examining the quality of their processes both on paper and in practice.

4.1.1. The Documentation-based Review

All of the sponsor's management system documentation is stored on the company intranet, categorised according to business function. However, when trying to source AMS documents, it was immediately clear that no section of the management system existed for AM. As discussed in section 2.2, in the early stages of this project AM had only recently gained prominence in academia and industry (Komonen, 2012, O'Hanlon, 2015, El-Akruti and Dwight, 2013), so perhaps the sponsor had not yet encountered AM as a discipline (or they had dismissed it as unimportant). This was also apparent in the way that the management system was structured, defining business functions as either “primary” or “support” processes (Anonymous, 2013a). This is a traditional method for categorising business functions in manufacturing, first introduced by Porter (1985), which is increasingly being recognised as outdated according to the AM community (Liyanage, 2012, El-Akruti et al., 2013). This traditional approach encourages organisations to consider support functions, such as maintenance, as a “necessary evil” – i.e. a cost which must be minimised – so that investment can be concentrated on more “value-adding” primary processes such as operations, logistics and sales (Liyanage, 2012, El-Akruti et al., 2013). AM thinking instead argues that support processes play a highly important role, and are vital in enabling organisations to deliver value; their performance has a direct impact on the business success and they must be given sufficient investment and senior management focus (Kennedy, 2015; O'Hanlon, 2015).

Therefore perhaps due to a lack of awareness, the sponsor did not explicitly have a documented AMS. However, as an asset-intensive business they clearly must have had systems and processes in place to manage their assets, and these were likely to be documented to some degree. A preliminary scan of the sponsor’s management system showed that such documents did exist, but that they were spread throughout various other functional areas (e.g. maintenance, operations, projects etc.). Therefore, each of the sponsor’s functional management systems were investigated more thoroughly to determine which ones contained relevant documentation that would qualify as part of “the sponsor’s existing AMS”.

This preliminary investigation found that six of the sponsor’s existing functional management systems contained documentation that was applicable to the management of assets (i.e. the “Global”, “Logistics (Planning)”, “Operations”, “Procurement”, “Projects”, and “Maintenance” Management Systems). Therefore each of the documents found in these systems were included in the documentation-based review of “the sponsor’s existing AMS”.

The codebook that was developed in section 3.2 of this report (see Appendix A) was utilised to carry out the assessment of these documents against the requirements of ISO 55000. Recall that this codebook was developed via the qualitative analysis of ISO 55000 and all other AMS requirements frameworks that were available in the literature. Each AMS requirement was concisely summarised and assigned with a unique code, which was then compiled into a hierarchical structure, providing a clear and concise representation of the ISO 55000 requirements. All documents from each of the 6 management systems identified above were analysed using the same coding process in order to assess their alignment with the ISO 55000 requirements, as defined in the codebook. The same descriptive coding methodology was utilised (Saldaña, 2011; 2014; Tracy, 2013; Yin, 2015) (see section 3.1.4 for an example), except that rather than looking for AMS requirements, the purpose was to find evidence of processes or systems that met those AMS requirements.

4.1.2. The Practices-based Review

As discussed in section 2.1, the sponsor company operates several manufacturing sites around the world. However, only its existing UK site was included in the practices-based review for the following reasons:

1. The sponsor's new facility will also be located in the UK; therefore they will both operate under the same legislation (whereas in other countries the regulations will differ). Clause 4 of ISO 55000 requires businesses to understand the organisational context, including the requirements of key stakeholders (British Standards Institute, 2014b). For high-hazard businesses such as the sponsor (an operator of nuclear facilities), regulatory compliance is of critical importance and one of the most important stakeholders is the governing regulatory body. Their requirements consequently have a huge influence on the design of several AMS components and processes. Therefore in different countries, were the regulators are different, the effect on the design of the AMS can be significant – for example, the UK nuclear regulator mandates that:
    - specific maintenance and inspection routines are in place for certain asset types
    - specific competency requirements are met for key organisational roles
    - specific information retention and reporting processes are in place
    (Office for Nuclear Regulation, 2016)

    Recall from the beginning of section 4 that if any of the sponsor's existing AMS processes were found to be acceptable in their current form, they would be adopted at the new facility. Therefore it made more sense to assess the practices at the UK site, which operates within the same regulatory framework, because their AM practices were more likely to be suitable.

2. The author of this research is based at the sponsor's UK site, therefore it was more practicable, from both a cost and time viewpoint, to gain access the UK site to carry out an assessment. Language difficulties and security clearance issues would have also been a negative factor at the sponsor's Dutch and German sites.

However, it was realised that carrying out a thorough practical assessment of the sponsor's organisation would be beyond the scope and capability of this research project without significant external assistance. Even when restricting the assessment to the UK site only, it would still need to cover multiple processes and systems from the various business functions associated with AM; therefore, a large team of AM experts would be required, each with sufficient knowledge and experience of good AM practice in the nuclear industry. Fortunately, an opportunity to utilise external assistance on this matter was available during the early stages of this project. In 2013, a business-critical incident occurred at the sponsor's UK site that was attributed to a significant AM failure (Anonymous, 2013b). Power was suddenly lost to the site and all backup systems failed to engage, causing a significant portion of the site's critical assets to be damaged beyond repair (note that this incident validates the observations made earlier in section 4.1.1, regarding the sponsor's lack of awareness of AM – and with significant consequences). In response, a thorough audit of the sponsor's existing AM practices was sanctioned by senior management. This audit was conducted in 2014 by an external consultancy firm, utilising an assessment methodology derived from the Institute of Asset Management's self-assessment tool (Institute of Asset Management, 2019). This was based on the requirements of PAS 55 (Anonymous, 2014a), which as discussed earlier in section 3.1.1, is the predecessor to ISO 55000 and is very similar in content. The audit identified multiple gaps in the sponsor's AM practices, and made several recommendations for improvement. Therefore, due to the difficulty in executing such an assessment as a part of this project, the results and recommendations of this external audit were utilised instead to identify the gaps in the sponsor's AMS from a practical standpoint.

4.1.3. Limitations

One limitation of the methodology described above was that the external audit results were secondary data, and this could have potentially weakened any conclusions that were drawn from the practices-based review. To resolve this issue, the author's own observations and knowledge of the sponsor's existing AM practices were utilised alongside the audit results. The author was employed by the sponsor, at the UK site, working in the field of AM, and was therefore well aware of the business's existing AM practices. Therefore, for each gap that was identified by the audit, the author's own knowledge and observations were utilised to provide further evidence wherever possible.

Another potential limitation was that the external audit, which was based on PAS 55 (Anonymous, 2014a), utilised slightly different assessment categories to those that were used in the documentation-based review (which as discussed in section 4.1.1 was based on ISO 55000 via the codebook). To resolve this issue, the questions within each assessment category from the external audit were analysed to determine where they aligned with the ISO 55000 categories used in the documentation-based review. The results of this analysis showed that three ISO 55000 assessment categories were not covered by the external audit, i.e.:

1. **B** – Determine the scope of the AMS
2. **T** – Develop an Internal Audit Process
3. **U** – Develop a Management Review Process

Therefore, these three areas could not be included in the practices-based review of the sponsor's AMS – they only had a documentation-based assessment. However, this was considered acceptable for the following reasons:

- **(B):** An AMS scope definition is entirely a matter of documentation anyway; it is purely a written statement with no directly associated practical element.
- **(T) and (U):** Solutions for these AMS components were already being developed by others in the sponsor's organisation. Many of the other ISO standards, such as ISO 9001 (Quality Management) and ISO 14001 (Environmental Management), also require Internal Audit and Management Review processes (British Standards Institute, 2015c; 2015d). These management systems were already under development for the sponsor's new facility (by others), and any common components such Internal Audit and Management Review were to be integrated into a single shared process (e.g. the organisation intended to carry out a single Management Review of all Management Systems together). Therefore it was not necessary to develop separate processes specifically for the AMS in these areas.

Therefore, it was considered acceptable to proceed with practices-based review, despite the three gaps in the external audit assessment criteria.

4.1.4. Prioritisation of the Identified Gaps

After reading the external audit report, it was clear that a significant number of gaps were likely to be identified by this assessment. Faced with the possibility that there would be too many gaps to be resolved during this research project, it was decided that each gap should be prioritised so that research effort could be targeted at the areas where improvement was most needed.

This was achieved by analysing the results of the documentation-based review and practices-based review together, and making an overall judgement on the level of risk posed for each AMS component: i.e. the likelihood and potential consequences for the business if the identified gaps were not resolved. The following risk matrix was utilised, as recommended by Hastings (2010) for the judgement of risk in an AM context:

		Consequence				
		Insignificant	*Minor*	*Moderate*	*Major*	*Severe*
Likelihood	*Almost Certain*	Medium	Medium	High	High	Extreme
	Likely	Medium	Medium	Medium	High	Extreme
	Moderate	Low	Medium	Medium	High	High
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	Medium	Medium

Fig. 4 – Matrix used to assess the level of risk associated with the gaps in the sponsor's existing AMS, adapted from Hastings (2010)

A risk score was given for each AMS component based on Fig. 4. The following possible consequences were considered in each case, also as recommended by Hastings (2010):

- Loss of business;
- Legal liability and costs;
- Loss of reputation;

- Lost production;
- Project failure, delays or additional costs;
- Emergency service costs;
- Repair costs;
- Secondary damage;
- Adverse environmental impact;
- Severe injury or loss of life.

This approach had some limitations, in that the risk matrix adapted from Hastings (2010) is unconventionally asymmetrical without justifying why (i.e. "Likely" x "Severe" = "Extreme", yet "Almost Certain" x "Major" = "High"), and the boundaries between the 5 options on each axis are entirely subjective because there are no clear definitions provided. This leaves the overall risk decision open to interpretation and subjectivity. To counter this, the justifications behind each decision were clearly presented in full detail to the sponsor company, so that they could challenge the conclusions if necessary (Catt, 2015a). For example:

Risk Assessment of the gaps in AMS Component N:

Likelihood = likely; Consequences = minor; ***Risk = Medium***

The specific documents required by ISO 55000 (i.e. the policy, scope, strategy) are intended to clearly describe the processes that make up the AMS. However, these processes can still exist and can function effectively without any documentation in place to describe them; the documentation itself exists mostly for auditing purposes. Therefore missing documentation can have only minor consequences – it is the effectiveness of the AMS processes that counts (and these are covered elsewhere in this assessment). [The Sponsor's] existing processes for identifying documentation requirements were found to be inadequate; therefore if they were adopted at [the new facility], it is likely that these minor consequences would occur (e.g. an audit failure): therefore a "medium" risk score was allocated based on Fig. 4.

4.2. *Results*

For the documentation-based review, 73 internal company documents were reviewed as part of the six functional management systems identified in section 4.1.1 (for confidentiality reasons they cannot be referenced here). Each document was assessed against the codebook (as defined in the methodology in section 4.1.1), to determine if any ISO 55000 requirements were met. The documents that typically met ISO requirements included high-level policies, procedures and standards that described AM processes and systems. Some documents did not meet any ISO 55000 requirements, and typically these included detail-level documentation such as technical specifications and instructions that did not define any AM processes or systems (they were typically the outputs of these systems).

For the practices-based review, the results of the external audit were utilised as defined in the methodology (see section 4.1.2). These results consisted of a score out of 5 for each assessment category, supplemented by a series of comments made by the auditors during their assessment (Anonymous, 2014a). The author's own observations were also utilised as further evidence, where available.

4.3. *Analysis*

The results of the documentation-based review and the practices-based review were analysed together to identify the gaps in the sponsor's existing AMS. Conclusions were drawn at an AMS component level (as defined in the codebook developed in section 3.2), i.e. the overall risk presented to the business due to the extent of the gaps in each AMS component (in accordance with the risk matrix shown earlier in Fig. 4). A summary of these findings is presented below in Fig. 5. For reference, a full description of each AMS component is shown in Fig. 6.

		Consequence				
		Insignificant	*Minor*	*Moderate*	*Major*	*Severe*
Likelihood	*Almost Certain*				M, S, V, W	P
	Likely		N		A, G, H, K, L, Q	
	Moderate			C		F
	Unlikely			O	B	
	Rare			I, T, U	D, E, J, R	

Fig. 5 – The level of risk associated with each component of the sponsor's existing AMS

A	**Determine the organisational context and how this should impact AM decisions**
B	**Determine the scope of the AMS**
C	**Leaders must show commitment to the AMS**
D	**Define an AM Policy**
E	**Define AM Roles & Responsibilities**
F	**Develop a Risk Management process for AM**
G	**Develop a process for setting AM objectives**
H	**Develop plans to ensure that AM objectives are achieved**
I	**Develop a process for Resource Management**
J	**Develop a Competency Management Process**
K	**Raise Awareness of the AMS**
L	**Determine the requirements for AM Communication**
M	**Develop a process for managing AM Information**
N	**Determine AM Documentation Requirements**
O	**Develop a process for managing AM Documentation**
P	**Develop processes for the Planning and Control of AM activities**
Q	**Develop a Management of Change Process**
R	**Develop an Outsourcing process**
S	**Develop processes for Performance Measurement and Reporting**
T	**Develop an Internal Audit Process**
U	**Develop a Management Review Process**
V	**Develop a process for determining Corrective Action in the Event of Failure**
W	**Deliver Continuous Improvement**

Fig. 6 – The 23 core AMS components from the codebook (see Appendix A), based on ISO 55000

4.4. *Conclusion*

As shown above in Fig. 5, a substantial portion of the sponsor's existing AMS was found to be inadequate, to the degree that if their existing practices were adopted at their new facility it would cause significant risk to the business. However, it was also recognised that it would not be possible to resolve all of the identified gaps as part of this research. The next section of this innovation report will explain how the Research Question defined earlier in section 2.3.1 was revised to enable the remainder of this project to focus on resolving the higher risk areas shown in Fig. 5 as a priority.

4.4.1. Innovations

In section 3.4.1, the codebook that was developed via an analysis of all AMS requirements frameworks available in the literature was claimed as an innovation, on the grounds that it is a useful assessment tool for determining if an AMS meets the requirements of ISO 55001. It presents the requirements of the ISO standard in a concise manner with a very clear structure, enabling the user to assess an AMS much more easily than they could if utilising the source document (which is poorly structured with a great deal of repetition and internal cross referencing). The work described in this section strengthens this claim, because it demonstrates that the codebook can indeed be utilised to carry out such an assessment, by providing a detailed example from a real industrial case.

5. Revised Problem Definition and Scope of Proposed Solution

Recall that an initial Research Question was defined in section 2.3.1:

> ***How can [the sponsor company] develop and implement an Asset Management System for [its new facility] that fully complies with all requirements of the ISO 55000 standard?***

And that this Research Question relied on 2 assumptions:

1. That ISO 55000 would be proven to be the most suitable framework on which to develop the sponsor's new AMS.
2. That developing an AMS for the sponsor's new site would be a feasible research aim, which would involve filling several moderate gaps in the sponsor's existing AMS.

Whilst assumption 1 was proven to be valid in section 3 of this report, assumption 2 was found to be invalid in section 4 – i.e. the sponsor's existing AMS was found to be woefully inadequate, to the extent that it would not be possible to resolve all of the gaps found within the scope of this project. This view was also shared by the sponsor company when they were presented with the results shown in Fig. 5; therefore, it was decided that this project should focus only on the most urgent, high-risk gaps, in order to make the most effective contribution to the business. And as well as focusing on a smaller selection of high-priority areas, the aim of the project was also adjusted so that it would develop a global solution for all of the sponsor's sites, rather than just for the new facility, so that the entire business could benefit.

Consider also that, as discussed in section 4, some of the gaps in the sponsor's existing AMS were documentation-based (i.e. due to their poorly documented AMS) and some were due to the poor practices found on site (i.e. sub-optimal implementation of processes and systems). To solve the documentation-based gaps, a suite of new AMS documentation would be required to define the sponsor's policy and strategy for AM, and to explain how they would meet all of the ISO 55000 requirements. Whilst this was recognised as a necessary piece of work, it was also considered to be a relatively trivial one that would not require an innovative, research-based solution. Therefore, the execution of this task – i.e. the writing of new AMS documentation for the sponsor to guide the business towards an ISO-compliant solution – was carried out by the author outside of the scope of this project (Catt, 2015b; 2015c; 2017).

The development of these documents will not be discussed as part of this report because their development did not require research.

It was recognised that the more challenging task would be to address the practices-based gaps, by designing new AM processes and systems and then implementing them at the sponsor's sites. If successful, these solutions would be far more beneficial for the business and would drive a genuine, demonstrable improvement in AM performance. Therefore, in order to deliver the maximum value to the business, it was decided that this project would focus on developing solutions for the gaps identified in the practices-based assessment only, because these gaps were more significant and complex, and would require in-depth, research-based solutions with more scope for innovation.

5.1. *Redefining the Problem*

Due to these changes in the project scope, the problem that was defined earlier in section 2.3 had to be revised, along with the Research Question. The next section of this report will show how a much more suitable problem definition was developed.

5.1.1. Problem Context 1 – The AMS Component(s) to address

The most significant gap, as shown in Fig. 5, was component P – i.e. the process for the planning and control of AM activities – therefore this gap was selected to become the main focus for the remainder of this project. However, it was also recognised that components M, S, V and W were the second highest risks, and therefore it would be more beneficial for the sponsor (as well as being more innovative) if a holistic solution was developed that incorporated all of these elements (it was recognised that components A, G, H, K, L, Q and F also scored the same risk rating of "High"; however, for component M for example this was made up of "Major" consequences and an "Almost Certain" likelihood, whereas for component A it was based on "Major" consequences and a "Likely" likelihood, which clearly represents a lower absolute risk if the axis were to be graded numerically). However, this approach would clearly only be feasible if components P, M, S, V and W were related in some way – i.e. if the outputs from one component formed the inputs to another (otherwise, such a holistic solution would itself contain gaps). To determine if this was the case, an analysis of the interactions between each AMS component was carried out. The codebook that was developed in section 3.2 (see Appendix A) was used to facilitate this analysis (recall that this codebook concisely summarises all of the AMS requirements that are found in ISO 55000, and structures them into 23 core AMS components).

After studying the codebook to identify the relationships between AMS components, it was evident that several of the requirements listed specified that the outputs from one component form the inputs to another: for example, there is a requirement for the AM decision criteria (i.e. an output from component A) to be utilised during the setting of AM objectives (i.e. component G) (British Standards Institute 2014b). It was recognised that a concise overview of these links for the entire AMS would be best presented diagrammatically. However, consider that the overview, principles and terminology section of the ISO standard already contains a diagram that attempts to show some of these relationships (British Standards Institute, 2014a) – however, it was not considered to be detailed enough, and nor does it cover all of the 23 AMS components identified by this research (see Appendix A). Therefore, this diagram was significantly expanded, by utilising the codebook, to identify all relationships that exist between each of the 23 AMS components (see Fig. 7 below). Wherever an output from one AMS component was found to be specified as an input to another component in the codebook, it was represented by a grey arrow in Fig. 7. The diagram also utilises the same high-level PDCA (Plan, Do, Check, Act) structure that is common to all ISO standards (British Standards Institute, 2013; 2015e), which is represented by blue arrows. Note also that the life-cycle stages included in the diagram have been limited to the asset utilisation phase only in order to align with the scope of this research (as discussed earlier in section 4.1.3).

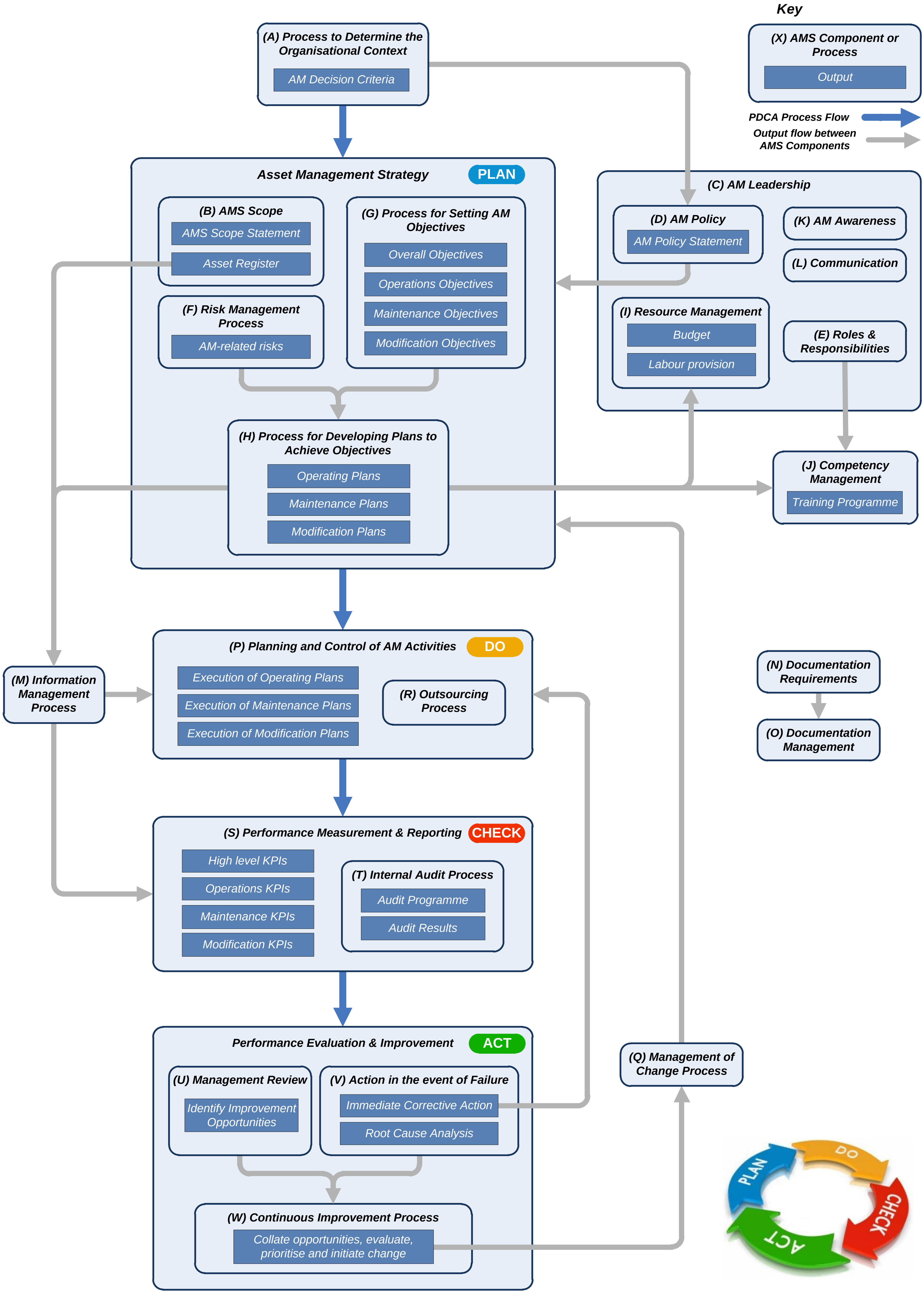


Fig. 7 – The 23 AMS components, with relationships and dependencies, adapted from ISO 55000 (British Standards Institute, 2014a)

Note that, according to Fig. 7, the following AMS components interact with component P as follows:

- **M – Information Management Process**: This must be designed in such a way that it provides component P with the information required to effectively plan and control AM activities, i.e.:
    - the required activities as specified in the plans from component H
    - the Asset Register as defined in component B
- **R – Outsourcing Process**: Outsourced activities and resources must be fully integrated into component P so that they are appropriately planned and controlled alongside insourced work.
- **S – Performance Measurement and Reporting:** This process must be designed in such a way that it can measure the outputs of component P and highlight any performance issues so that improvement can be achieved.
- **V – Action in the event of failure**: Component P must be designed in such a way that it can accommodate any "Immediate Corrective Actions" that arise from component V – i.e. it must be able to plan and control this reactive work alongside the planned activities from component H. It must also be able to feed failure information forward to component V so that root causes can be eliminated to drive improvement.
- **W – Continuous Improvement:** Consider also that component W, although not directly connected to component P, is a common output of both S and V as discussed above (i.e. the purpose of both performance measurement and root cause analysis is to drive improvement) – therefore it is feasible to include W within the solution scope.

There are of course other areas of the AMS that have links to P, but they were considered too distant or indirect to be feasibly included within the research scope. For example, Component A (i.e. Determine the Organisational Context), which involves considering key stakeholder's requirements for AM, as well as other organisational strategies (e.g. Risk policy, Quality Management System etc.), clearly has a strong influence on the AM Strategy – which in turn influences the AM Objectives and ultimately the scope and volume of activities that must be delivered by component P. However, the aim here is to focus on the most urgent gaps in the sponsor's AMS – not to develop the entire solution – therefore a line must be drawn to prevent too many subjects from being included in the research scope. Only direct links from adjacent components in Fig. 7 were considered.

Note that component R, although closely linked to P, was one of the lowest risk areas according to Fig. 5 – therefore including it within the solution scope was not considered to be a priority; the sponsor's existing processes in this area were found to be of a reasonable standard and posed little risk with respect to AMS performance. However, whilst the development of a full outsourcing solution was not considered to be necessary, it was recognised that some elements of an outsourcing process could have a direct impact on component P (particularly in contexts were the execution of AM activities is outsourced), and therefore it would be necessary to include these elements within the solution scope anyway, at least to a limited degree.

Similarly, it was recognised that this same principle could be applied to all of the AMS components listed above – i.e. they each interact with component P to varying degrees, therefore it was not clear exactly to what extent they needed to be included within the project scope, in order to deliver an effective solution. Therefore it was recognised that a review of the literature would be required to determine exactly which elements of the 5 AMS components listed above needed to be included within the project scope, in order to define clear boundaries for the solution (see later in section 5.3).

In summary, this research project needed to develop a combined solution covering all 6 AMS components (i.e. P, M, R, S, V and W). This would deliver the maximum benefit for the sponsor in the time available by tackling multiple high-priority, interlinked AMS components within a single holistic solution. The primarily focus would be on the highest priority area – i.e. P, the planning and control of AM activities – and this subject would be covered in depth. Elements of components M, R, S, V and W would also be included where it was appropriate and beneficial to do so; the precise solution boundaries would be determined by reviewing these subjects in detail in the literature (see section 5.3).

5.1.2. Problem Context 2 – The Life-cycle Stage(s) to address

Another issue highlighted by Fig. 7, is that for some AMS components a single process can serve all life-cycle stages – whereas for others, separate processes are needed for each stage of an asset's life. For example, for component F it would be reasonable for a single Risk Management Process to be in place to collate and assess all risks related to AM, and then to feed them into component H (where plans would be put in place to control these risks). However, for component H a single process would not be suitable, because each life-cycle stage has its own unique planning requirements: e.g. they need to cover fundamentally different types of activities, meet different objectives, and would therefore require different processes for development. Other similar cases where separate processes are required for each life-cycle stage are clearly shown in Fig. 7 (i.e. where there are separate outputs for each life-cycle stage).

Note that component P is one such case, where the activities carried out during the different life-cycle stages (e.g. operations, maintenance, modification) need to be managed by separate planning and control processes. This is because they need to control different types of activities with different types of resources over different timescales, and therefore separate processes are required to accommodate these specific requirements. Therefore in the context of this research, separate solutions would be required for each life-cycle stage. However, the development of multiple solutions for all life-cycle stages (in sufficient depth) was not considered to be achievable within the scope of this project. Therefore, the focus of this research was directed towards developing a solution for a single life-cycle stage only – i.e. maintenance – due to the following reasons:

- It was discovered during the assessment of the sponsor's existing AMS (see section 4), that their existing process for the planning and control of maintenance activities was largely ineffective, therefore the gap was more significant in this area. By using their existing process, the sponsor's UK site was overwhelmed with breakdowns and could not utilise their resources effectively to manage the volume of work; therefore a solution for maintenance was considered to be more pressing than for the other life-cycle stages. Such a solution would be useful for both the sponsor's new facility and for their existing sites, providing an opportunity for this project to deliver significant AM improvement across the entire business.
- As discussed in section 2.2, the subject of AM is more established within the maintenance community, and has been practiced by maintenance professionals for a number of years. For example, AM conferences and seminars are generally targeted at a maintenance audience (DFA Media, 2016, Institution of Mechanical Engineers, 2016) and many maintenance societies and institutions also cover the discipline of AM (The Irish Maintenance and Asset Management Society, 2014, Global Forum on Maintenance and Asset Management, 2016; European Federation of National Maintenance Societies, 2018). Therefore it was considered more likely that existing research would be available for the planning and control of AM activities in a maintenance context, which could be utilised to develop a solution.

- The author, who is a maintenance professional, has far more knowledge and experience in this particular life-cycle stage; therefore it was beneficial to be able to utilise this knowledge during the development of a solution.

5.1.3. Defining the Research Subject

The Global Forum on Maintenance and Asset Management (GFMAM) defines 39 AM subject areas in their principal publication, the AM Landscape (GFMAM, 2014). One of these subjects – "Maintenance Delivery" (MD) – concerns the planning and control of AM activities in a maintenance context. Therefore the term MD will be utilised from this point forwards to describe the subject area of this research project. According to the GFMAM (2014), MD involves managing the execution of maintenance activities (i.e. component P), including both preventive and corrective tasks (i.e. component V). It involves ensuring that sufficient labour is available to carry out these activities (i.e. component R), whilst also considering the infrastructure of the supporting Maintenance Information Systems (i.e. component M). The fact that the formal definition of this subject does not include components S (i.e. Performance Measurement) and W (i.e. Improvement), nor the root cause elimination element of component V, allowed this research to take the subject further than usual, by incorporating these elements into the solution – which presented an opportunity for innovation.

5.1.4. Problem Context 3 – the issues raised by a multi-site problem

As discussed at the beginning of section 5, the aim of this research was adjusted in order to develop a global solution for all of the sponsor's sites, rather than just for their new facility. However, when assessing the sponsor's existing AMS (see section 4), it was evident that from a MD perspective, they had already been utilising a global, aligned process at all sites for many years (Anonymous, 2013c). Of course, the assessment carried out in section 4 highlighted significant gaps in this established MD process – one of the most significant criticisms being that it was highly informal and defined the process only to a very vague level of detail, which led to poor practices being implemented at the sites (Anonymous, 2014a).

Initially, a solution to this problem was proposed that involved developing a more detailed MD process for the sponsor, utilising best practice, and then implementing it at all sites. Before developing a solution, a discussion was held with each site's Maintenance Manager in order to gain more understanding of their requirements. Through this process it was discovered that a single, globally aligned MD process would not be effective, because each site was found to have very different existing processes for planning and controlling maintenance activities, e.g.:

- they had different processes for work identification, decision making and approval;
- there were differences in the level of detail during planning and scheduling;
- they had different organisational structures with different quantities of planners and technicians, with varying levels of outsourcing and in-house skills;
- there were differences in the configuration of the supporting maintenance software, and in the scope of performance measurement and reporting.

The reasons given by the Maintenance Managers was essentially one of *context* – each site had historically developed their own unique MD methodologies as a consequence of operating in different environments (i.e. in different countries with different external stakeholders and regulations, with different asset ages and technologies, with different organisational structures and cultures). For example, legal requirements in Germany mandate that specific data is recorded for all plant defects and sent directly to the nuclear regulator, in a very specific format (Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety, 1992) – and this understandably had a direct impact on the design of their MD process.

This explained why the sponsor's existing global MD process was so generic. All sites were obligated by senior management to align their processes, in order to "drive up standards". To facilitate and demonstrate this alignment, they were required to define and commit to a global MD process covering all sites. But of course, due to their contextual differences, this was essentially an impossible task – therefore the agreed "global" process had to be written in a deliberately generic manner, containing only very high-level requirements, precisely to enable each site to "comply" whilst retaining their local contextual differences. As a result, it provided little or no guidance on appropriate MD practices – and over time, this lack of detail had resulted in the unchecked implementation of poor practices in several areas, ultimately leading to the poor performance seen in Fig. 5.

Therefore, it was recognised that if this project simply developed a more detailed global MD process for the sponsor, and then forced all sites to align – it would not solve the problem. As shown above in the German example, in some cases specific MD practices can genuinely be necessary to satisfy local contextual requirements. Furthermore, when reviewing MD processes from the literature (as will be seen in section 6 of this report), every process that was encountered was found to be different – there were some common core elements, but enough variation to mean that no two processes were identical. Every business or sector carries out MD in a slightly different way; there is no single "correct" answer.

This led to the conclusion that an effective multi-site MD process must not only be detailed enough to ensure that good practices are implemented, but also flexible enough so that it can adapt to suit the various contexts found at different sites. But if flexibility can only be achieved by simply leaving out the details, then the two requirements contradict.

5.1.5. The New Research Question and Research Aim

This led to the development of the following Research Question:

> ***How can a process be developed for Maintenance Delivery that is detailed and robust enough to ensure good practice, yet is still flexible enough to be effective in any context?***

The following Aim Statement was then developed in response to the Research Question:

> ***This project will deliver a comprehensive framework of MD practices containing multiple options from many different industries and sectors, from which the end user can make informed selections in order to develop a detailed business process that is tailored to suit their specific context.***

It was considered very unlikely that such a solution already existed to answer the research question, because any sufficiently detailed MD process that was already available would have been designed for a specific context, and therefore would not have been flexible – it would contain only one set of practices, which would not be suitable in all contexts. It was also considered unlikely that a single process would exist covering all of the AMS components that were defined in section 5.1.1 to be within the scope of the solution (i.e. P, M, R, S, V and W). These unique aspects of the proposed solution were confirmed during a comprehensive review of the literature that involved an analysis of all existing MD processes and frameworks (see section 6). All existing processes that were reviewed contained only a single set of practices, which would not be suitable in all contexts. Additionally, no single process was found that holistically covered the entire framework scope.

It was also recognised that such a framework could be utilised elsewhere, outside of the sponsor company, in any business that plans and controls maintenance activities. Therefore, because the proposed solution would be both unique and beneficial for many different industries and sectors, by developing such a solution this research would be delivering innovation and making a useful contribution to the wider AM field.

Note that from this point forwards, as a result of the revised Research Question, the title of this research project was changed to "A Tailorable Framework of Practices for Maintenance Delivery".

5.1.6. Research Objectives

The following Research Objectives (ROs) were established using Bloom's taxonomy (Anderson and Krathwohl, 2001) in order to drive the development of the framework:

1. *Review the literature to clearly define the scope and boundaries of the framework, focusing on the following AM subject areas:*
    a. *The Information Management System (M)*
    b. *The Outsourcing Process (R)*
    c. *The Performance Measurement and Reporting Process (S)*
    d. *The Failure Management Process (V), considering both:*
        i. *The management of corrective actions in the event of failure*
        ii. *The Root Cause Analysis of failures so that defects are eliminated*
    e. *The Continuous Improvement System (W)*
2. *Analyse the literature from within these defined boundaries to extract all MD practices and develop a preliminary version of the framework:*
    a. *Determine all detailed process steps required for a comprehensive MD process*
    b. *Determine which steps are core and which are optional, to enable tailoring based on local contextual requirements*
    c. *Ensure that each optional practice is accompanied by appropriate guidance to facilitate decision making*
3. *Develop the literature-based framework further by utilising expert opinion from industry:*
    a. *Revise any missing or incorrect practices to ensure that the framework is fully comprehensive and able to produce an effective MD process in any context*
4. *Apply the framework in the Sponsor Company; use it to develop and implement an improved MD process.*

5. *Evaluate the effectiveness of this implementation and demonstrate that it closes the MD-related gaps found in the Sponsor's AMS.*

The next sub-section of this report will describe how RO 1 was addressed – i.e. the definition of appropriate boundaries for the framework. This was achieved via a review of the literature, focusing on the subject area of MD and its interactions with AMS components M, R, S, V and W. During this process, several additional topics were encountered in the literature that were also found to have a significant impact on MD – namely Maintenance Requirements Analysis (MRA), Materials Management (MM), and Shutdown / Turnaround / Outage (STO) Management. Therefore these subjects were also reviewed to determine if it would be appropriate and beneficial be include them within the scope of the framework, and to what extent.

5.2. *Methods Selected to Address the Research Objectives*

Various research methods were employed throughout this project in order to address the Research Objectives; a summary is provided in the table below indicating the methods used in each case (see Table 33). Following the table is a review of potential alternative methods along with justification for each method chosen.

Research Objective	Methodology Employed
RO 1 – Define the framework scope and boundaries	Literature Review
RO 2 – Extract MD practices from the literature	Hierarchical Descriptive Coding
RO 3 – Extract MD practices from industry	Delphi methodology
RO 4 – Apply the framework in the sponsor company	Implement and test
RO 5 – Evaluate the impact of this implementation	Audit questionnaire

Table 3 – Summary of Methods used to address each Research Objective

5.2.1. RO 1 – Literature Review Methodology

At this point in the project, AM component P (i.e. the planning and control of activities) was already established as the main focus of the framework, as discussed earlier in section 5.1.1. However, several additional AM subject areas were recognised to have strong relationships with component P, and would therefore require some level of inclusion in the framework scope to ensure an effective and holistic solution. The aim of RO 1 was to establish exactly how much of these other subject areas should be included within the framework scope.

The chosen methodology for addressing this RO was to review the literature across all of the subject areas in question, to gain a full understanding of the interactions and effects that they have on the subject of MD. Any significant interactions and dependencies were included in the framework scope, and anything negligible was excluded. Each interaction's significance was determined by examining cases in the literature were their presence or absence was described as having a significant effect on MD performance.

An alternative method could have been to seek the advice of industry experts, perhaps via interview, to understand the boundaries of their existing MD processes, and then to adopt these boundaries for the framework scope. However, this approach would risk producing a framework that was limited in scope to existing practice. It was recognised that there would be a greater opportunity for innovation if the framework boundaries were defined from first principles, i.e. based on the practices that were actually shown to influence MD performance – even those from different subject areas. This would provide more opportunity for this research to go beyond the existing boundaries of the MD subject and develop a more effective solution that incorporated multiple additional AM subject areas.

5.2.2. RO 2 – Hierarchical Descriptive Coding Methodology

For RO 2, a methodology was required to extract and summarise all existing MD practices from the literature. Coding is a widely used technique for the qualitative analysis of literature, generally used for summarising and extracting meaning from a text (Saldaña, 2011; 2014; Tracy, 2013; Yin, 2015). The technique has many different variations; possible coding variants that were considered are detailed below with a brief definition provided in each case. This is followed by a critical discussion presenting the reasoning and justification behind the eventual selection decision.

- **"In Vivo" coding** (sometimes referred to as "literal" coding) is a type of coding that involves taking the code directly from one the words or phrases that are actually contained within the text (Corbin and Strauss, 2008; Saldana, 2009). It therefore focuses on the literal *content* of the text, and not necessarily on its *meaning*. **"Descriptive" coding** is the opposite approach to "In Vivo" coding, whereby the code's purpose is to summarise the meaning / topic behind the text, while the code itself may not necessarily be stated in the text directly (Saldaña, 2011; 2014; Tracy, 2013; Yin, 2015). Descriptive coding was selected for this case because there are multiple sources involved from many different industry backgrounds, and it was considered important to be able to identify equivalent meanings behind practices that might be phrased differently by different authors; the "In Vivo" method would not account for this due to the inevitable differences in phrasing between texts.

- **Process coding** is a technique that exclusively utilises codes ending in "ing" to denote actions (Corbin and Strauss, 2008; Saldana, 2009). Although at first this method seems to fit well with this research (i.e. the development of a business *process* design framework), it was considered too restrictive. There might be clearer or more logical code choices that could better convey the meaning of a text without using "ing".
- **Structural coding** is a technique whereby codes are mapped against the number of sources from which they are derived, to show frequency of occurrence (MacQueen et al., 2008; Saldana, 2009). This method was considered unnecessary in the context of this research objective – recall that the aim was to extract as many practices as possible, but not necessarily to infer their importance or significance based on frequency of occurrence in the literature.
- **Hierarchical (Axial) coding** is a method whereby codes are structured using a second level of coding into a hierarchy of categories (Tracy, 2013, Yin, 2015). This method is useful for grouping the codes together and forming categories or themes, and for this reason it was selected in order to provide some structure to the framework (i.e. sections and sub-sections).
- **Recursive Abstraction** is a process that has some similarities to coding (i.e. its purpose is to summarise the meaning behind a text) but it differs in its approach: data is summarised and then repeatedly re-summarised in an iterative fashion, resulting in a very compact summary that is easier to categorise and compare across different sources so that patterns can be identified in the data (Hershkowitz et al., 2001; Polkinghorne and Arnold, 2014). A common criticism of this method is that the final conclusion is several times removed from the original text, which increases the risk of losing the original meaning (Hershkowitz et al., 2001; Oun and Bach, 2014). In the context of this research, this technique is not appropriate as the practices being analysed do not require simplification – the intent is only to identify and extract practices, not to simplify them. The framework

needs to include a high level of detail so that the end user can fully understand the options available and create a detailed MD process.

The chosen methodology was a combination of descriptive coding and hierarchical (axial) coding. These methods were selected because they enable the identification and extraction of practices from the literature, while providing an effective way to identify equivalent meanings from difference sources across different industry backgrounds. The hierarchical element also helps to structure the extracted practices into categories, in order to enable the formation of the framework sections and sub-sections. The detailed application of the chosen methodology is described in full in section 6.1.

5.2.3. RO 3 – Delphi Methodology

For RO 3, a methodology was needed to develop and improve upon the initial literature-based framework design by utilising the opinions of industry experts. Possible methods that were considered for extracting expert opinion are listed below, with a brief definition provided in each case. This is followed by a critical discussion presenting the reasoning and justification behind the eventual selection decision.

- **Interviews** – i.e. one-to-one conversation between interviewer and interviewee with the intent of extracting qualitative data (Oun and Bach, 2014; Yin, 2015; Bhattacharya, 2017). This form of data collection is ideal for gathering in-depth information on individual perspectives and opinions, and can range in style from highly structured to unstructured (Yin, 2015; Bhattacharya, 2017). With structured interviews, a precisely worded and ordered set of questions is utilised to maintain consistency across all participants and to facilitate analysis of the collected data; however this style tends to favour only closed-ended questions with a limited range of responses (Yin, 2015; Bhattacharya, 2017). Unstructured interviews utilise a looser, free-flowing format that enable the interviewer to pursue any unexpected but relevant ideas offered by the interviewee (Tracy, 2013; Magnusson and Marecek, 2015). This lack of structure means that conversation is more likely to drift off-topic, but the relaxed style means that it is more likely to extract the truth, and is therefore ideal for gathering opinion data (Seidman, 2013; Yin, 2015; Bhattacharya, 2017).
- **Questionnaires** – are in essence a specific method for carrying out a highly structured interview as described above, adopting the same principles of precisely worded and ordered questions with a closed range of responses, only without the face-to-face

element (Brace, 2013; Saris and Gallhofer, 2014). Typically with a self-complete style, questionnaires can be delivered simultaneously and electronically to each participant and therefore consume less of the researcher's time when compared to a face-to-face interview (Okoli and Pawlowski, 2004; Ononiwu, 2013).

- **Delphi** – utilises a series of questionnaires or interviews to elicit expert opinion via an iterative, round-based approach (Erffmeyer et al., 1986; Hsu and Sandford, 2007; Aichholzer, 2009). Controlled feedback is provided to participants in between rounds, consisting of a summary of their opinion in comparison to the group average (therefore some level of statistical quantification is required); this encourages any outliers to adjust their views in order to align with the wider community (or else justify their differences), so that consensus draws closer as the rounds progress and opinions align (Okoli and Pawlowski, 2004; Miller, 2006; Skulmoski et al., 2007). Participant's responses are anonymous (i.e. they do not interact with each other directly), which removes any source of influence from dominant figures, allowing unusual or unpopular opinions to surface freely (Mullen, 2003; Ononiwu, 2013; Marchau and Van de Linde, 2016).
- **Focus Groups** – i.e. an interactive discussion between a pre-defined group of participants, focusing on a specific topic, and guided by a moderator (Morgan, 1998; Hennink, 2014; Yin, 2015). The concept is similar to an interview but utilising a group of participants at the same time, rather than on an individual basis (Morgan, 1998; Oun and Bach, 2014). The aim is to utilise interaction and discussion within the group to generate a wide range of ideas, perspectives and opinions, rather than to reach a decision or consensus (Hennink, 2014). The method is able to generate a wide range of data very quickly when compared to a series of individual interviews, although it will not achieve the same level of depth (Hennink, 2014; Yin, 2015).
- **Direct Observation** – i.e. systematically watching and listening to a phenomenon as it takes place and collecting data via field notes (Oun and Bach, 2014; Yin, 2015; Bhattacharya, 2017). In the context of this research, an observation approach would involve directly witnessing and recording MD practices as they are executed in industry. This would have the advantage that the data would be completely first-hand and unmodified by an intermediary person's (i.e. a participant's) agenda or interpretation (Yin, 2015). However, one limitation of this method is that people tend to change their behaviour when they feel that they are being observed – a problem which can be countered by having the researcher take an active membership of the group without the

other participant’s knowledge (Oun and Bach, 2014; Bhattacharya, 2017). Another limitation is that each instance of observation may get different results, depending on the time and place and coincidence; therefore multiple observation sessions are perhaps needed at different times to get a full picture, which is inevitably time consuming (Yin, 2015).

The chosen methodology was a Delphi approach, incorporating a mixture of unstructured face-to-face interviews and highly structured self-complete questionnaires. The ability to combine different interviews styles into the research design was considered valuable, providing a “best of both worlds” scenario (Lang, 1995) – i.e. beginning with an unstructured face-to-face interview with open-ended questions to gather initial opinions, and then refining and cross-checking these afterwards with highly structured follow-up questionnaires.

The Focus Group approach was considered potentially useful in that it would be a highly time-efficient way to generate a wide range of ideas, perspectives and opinions. However, it simply would not be logistically practical to arrange a gathering of multiple industry experts from different organisations in different countries with inevitably busy schedules. The Delphi approach was considered more realistic because participants don’t actually have to meet each other or be in the same place at the same time (Lang, 1995). A focus Group approach also carries the risk of strong personalities dominating the group and shutting down fringe opinions (i.e. a “bandwagon effect”) (Lang, 1995; Yin, 2015). By contrast, the anonymity principle of the Delphi approach effectively removes this element of bias and allows each participant to have their say.

It was recognised that the Direct Observation method could potentially provide the opportunity to witness and record new MD practices directly from an industry environment – which would be useful data for improving and constructing the framework. However, due to its inherent nature, this method can generally only gather data on processes and behaviours, and not on opinions (Oun and Bach, 2014), meaning that it would be unsuitable for obtaining expert’s views on the existing practices already gathered from the literature. Since it would only be able to partially answer RO 3, it was not considered a suitable option. The method would also be very time-intensive in comparison to interviews or focus groups, and require access to working areas of industry sites which are often off-limits for visitors.

The detailed application of the chosen Delphi methodology is described in full in section 7.1.

5.2.4. RO 4 – Implement and Test

For RO 4, a methodology was required to enable the application of the completed framework, to demonstrate that it could be successfully utilised to develop a MD process in a specific context. The selected approach was to implement the framework at one of the sponsor's sites; the details of this methodology are described in full in sections 9.1 – 9.4. An alternative approach could have been to implement the framework in a completely different business or perhaps in a range of different businesses (e.g. utilising the sites of the participants from the Delphi study). This approach would have provided greater evidence of the framework's capabilities, by demonstrating its application in a variety of different industry contexts. However, as well as being highly impractical (i.e. making significant organisational changes to an external company outside of the author's control), the sponsor of this research was clearly expecting this project to deliver results within their own business first – i.e. a closure of the gaps identified in the Problem Definition.

5.2.5. RO 5 – Audit Questionnaire

For RO 5, a method was required to evaluate the effectiveness of the implementation described above in RO 4, by demonstrating the successful closure of the MD-related gaps found in the Sponsor's AMS. The chosen methodology was to utilise the same set of audit questions that were utilised to identify the gaps in the original problem definition – in order to provide a direct "before and after" comparison. The detailed application of this chosen methodology is described in full in section 9.5.

An alternative approach could have been to measure and demonstrate an improvement in MD performance by comparison of empirical data before and after the implementation. However, this was not possible because no previous performance data existed with which to draw a comparison. As described earlier in section 4, an assessment of the sponsor's existing AMS revealed significant gaps in their performance measurement processes, to the extent that historical performance data was non-existent.

5.3. *Literature Review to Determine the Scope and Boundaries of the Framework*

The subject of MD was defined earlier in section 5.1.3 as the management and coordination of maintenance *activities* – i.e. the execution of work – including both preventive and corrective tasks (Global Forum on Maintenance and Asset Management, 2014). Businesses with large asset portfolios typically need to manage tens of thousands of maintenance activities every year, all of which must be executed within strict deadlines to ensure asset reliability, safety and legal compliance (Abramic-Dilger, 1998; Mosher, 2000; Tani, 2001; Suttell, 2005; Aoudia et al., 2008; Doyle et al., 2009). The challenge usually faced in industry is to manage this large volume of work with only a limited labour resource pool, and for this reason effective MD practices are essential for delivering resource efficiency and optimisation (Sahoo, 2008; Samaranayake and Kiridena, 2012; Shiver, 2017).

The specific elements of a MD process include: the detailed planning of execution methods, the estimation of resource requirements including labour and materials, scheduling and optimisation of these resources in line with task due dates, the control of work execution to ensure personal safety and job quality, and the capture of task data such as inspection findings, measurements and work history (Global Forum on Maintenance and Asset Management, 2014). Whilst it was clear that each of these MD elements needed to be included within the scope of the framework, the extent to which other related AM subjects needed to be included – i.e. those defined in section 5.1.6 – was unclear. Therefore the literature was reviewed and the following conclusions were drawn regarding how significantly these subjects impact MD, and therefore which specific aspects of these subjects needed to be included within the scope of the framework:

5.3.1. Information Management (AMS component M)

In order to effectively coordinate a large maintenance programme with a significant volume of activities, a substantial volume of data must be managed (i.e. asset data, task data, and resource data), and this is typically achieved via a Computerised Maintenance Management System (CMMS) (which can also take the form of a maintenance module within a wider Enterprise Resource Planning (ERP) system covering multiple business functions) (Suttell, 2005; Canaday, 2008; Sahoo, 2008; Ononiwu, 2013; Van der Westhuizen and West, 2016). Fundamental CMMS functionality includes the ability to create an asset register to store equipment data (Sahoo, 2008; Ismail, 2014; Duffuaa and Raouf, 2015) and the ability to use Work Orders (WOs) to electronically plan and control maintenance activities (Campbell and Reyes-Picknell, 2006; Shafeek, 2014; Duffuaa and Raouf, 2015). This functionality aligns with the requirements for component M as shown in Fig. 7 (see section 5.1.1), i.e. the system must manage asset register information from component B and maintenance plan information from component H.

Several authors recognise that an effective CMMS is critical to the success of any MD process (Cooper, 1998; Shafeek, 2014; Duffuaa and Raouf, 2015), yet most CMMS software packages are unable to perform effectively "out of the box" – they often require significant customisation during implementation to suit the specific business process that they are supporting (Campbell and Reyes-Picknell, 2006; Sahoo, 2008; Samaranayake and Kiridena, 2012; Duffuaa and Raouf, 2015, Summerfield, 2015). Furthermore, the literature also says that CMMS implementations often fail to achieve this alignment with the MD process (Bannister, 1996; Cooper, 1998; Westerkamp, 1998; Campbell and Reyes-Picknell, 2006; Ononiwu, 2013; Duffuaa and Raouf, 2015; Summerfield, 2015); several specific cases were found where poor CMMS implementation was cited as a direct cause of poor maintenance performance (Swanson, 1997; Aoudia, Belmokhtar and Zwingelstein, 2008; Canaday, 2008) (note that another case in point is the sponsor of this research, as seen in section 4). Typical symptoms include an over-complex CMMS that is difficult to use and where data cannot be entered or retrieved easily when required (Kherun et al., 2002; Sahoo, 2008; Fernandez and Marquez, 2012; Duffuaa and Raouf, 2015).

In summary, to address the RO in this area, the effectiveness of a MD process is very dependent on the supporting information management system – i.e. the CMMS. This system must be implemented and configured carefully so that it closely aligns with the MD process that it is supporting, in order for it to be successful. However, this close alignment is frequently not achieved in practice, resulting in poor performance in many businesses. There is clearly a gap here in common practice, in that there is a consistent poor link between business process design and CMMS capability. To resolve this common industry problem, a solution will be needed to assist with CMMS implementation and configuration so that successful alignment with the MD process is more easily achievable. This presented an opportunity for this research to take on an additional objective in order to deliver an innovative solution. Therefore, alongside a tailored MD process, the scope of the framework was expanded so that it would also generate a fully aligned implementation specification for the supporting CMMS, which is also tailored according to the same contextual requirements. This will enable the end user of the framework to not only create a tailored MD process, but also ensure that they are able to purchase, implement and configure a CMMS that has all of the necessary functionality to fully support that process. This was a novel approach – by combining a business process design tool with a software specification tool – to solve a common industry problem.

5.3.2. Outsourcing (AMS component R)

The supply of adequate labour resources is an essential part of MD, whether those resources are sourced internally or externally (Keizers, Bertrand and Wessels, 2003; Shafeek, 2014; Duffuaa and Raouf, 2015). The level of outsourcing usually varies depending on the context; for example, high levels of outsourcing are more common in certain sectors such as Facilities Management (Kherun et al., 2002, Suttell, 2005). However, regardless of the level of outsourcing, from a MD perspective the process is the same – both internal and external resources must be planned and controlled together in order to deliver an effective maintenance programme (British Standards Institute, 2014b). The only difference being that external services must be identified as such in the CMMS so that maintenance expenditure is correctly recorded (Wulff, 2005; Sahoo, 2008; Lachance, 2012; Shafeek, 2014).

Therefore the planning and control of outsourced labour was included in the framework scope, alongside insourced labour. However, the commercial aspects of outsourcing, such as the agreement of service contracts and supply arrangements, was excluded from the scope. These were recognised as one-off activities that are carried out in advance, and do not fit into a continuous, day-to-day, operational process like MD due to differences in timescale. Also, as discussed in section 5.1.1, these aspects of the sponsor's existing outsourcing process were found to be of a reasonable standard already, and posed little risk to AM performance.

5.3.3. Action in the event of failure (AMS component V)

Recall that this part of RO 1 has two elements:

i. *The management of corrective actions in the event of failure*
ii. *The Root Cause Analysis of failures so that defects are eliminated*

In the context of maintenance, "failure" refers the breakdown of an asset, and "corrective action" signifies the response to this failure – i.e. the reactive repair of the failed equipment (Kherun et al., 2002; Institute of Nuclear Power Operations, 2010; Peters, 2014). It is common practice for these corrective tasks to managed as part of a MD process (Keizers, Bertrand and Wessels, 2003; British Standards Institute, 2009; Baker, Booth and Wilson, 2013); therefore to address part "i" of the RO above, it was decided that the framework developed by this research would simply include its own section for the management of “Emergent Work”. Note that for the purposes of this research, the term “emergent” is preferred rather than “breakdown” or “corrective” work, because MD also includes the management of partial failures / defects (i.e. not exclusively “breakdowns”), and the management of condition-based responses that are pre-emptive of failure (i.e. not exclusively “corrective” work). The one characteristic that all of these types of maintenance have in common is that they are all non-routine; they are non-cyclic; they emerge without a consistent pattern – hence the term “Emergent Work” is preferred, as used by Baker, Booth and Wilson (2013).

Regarding part “ii” of the RO above: it is recognised by several sources that in the event of asset failure, it is insufficient to respond only with an emergent repair task. Yes, the failed asset must be repaired, but it is vital that an investigation also takes place to identify the root cause of failure, and eliminate it to prevent recurrence (Sharma and Sharma, 2010; Port, Ashun and Callaghan, 2011; Jackson, 2016). If sufficient time is not made for eliminating the root causes of failure, then reliability performance deteriorates, the number of failures increases, and consequently there is even less time available for root cause analysis (RCA) in the future – i.e. there is a downward spiral effect (Jackson, 2016). Time and resources are entirely consumed moving from one crisis to the next, i.e. a fire-fighting situation. To avoid this downward spiral, it is essential that RCA is given sufficient attention; however, this is not always possible in reality because in most cases, the people who are most equipped to carry out an effective RCA investigation are the same people who are busy executing maintenance tasks (Latino, 2000; Port, Ashun and Callaghan, 2011; Jackson, 2016). However, because the same resource pool is stretched across both activities, there is actually a good opportunity to manage them together using the same process – for example, Jackson (2016) suggests the use of a CMMS Work Order to plan and execute RCA investigations. Therefore in this project, there was a clear case for integrating the management of RCA activities into the MD framework, so that every failure can be logged, investigated and analysed to deliver improvement – as a core part of normal work processing.

However, this integration of RCA into the MD framework was limited to the planning and coordination of RCA activities only – the selection of a specific RCA methodology was excluded. This was because a multitude of RCA techniques were encountered in the literature – from “5Y” (Katzel, 1996; Pylipow and Royall, 2001; Okes, 2005) to the “Ishikawa Fishbone” (Hambleton, 2005; Fernandez and Marquez, 2012; Barsalou, 2016) to “Fault Tree Analysis”

(Sharma and Sharma, 2010; Okes, 2005; Nailen, 2015) – each with their own strengths and weaknesses. However, it was not clear from the literature as to which technique is the most effective, because this varies depending on the context (Nailen, 2015); therefore the end user should be free to define this for themselves in each case. Consider that the exact method for the execution of a maintenance task is not dictated at a business process level; this is determined during the execution of one of the process steps (e.g. "plan task execution method"); therefore the same principle should apply to the selection of an RCA methodology.

In summary, a detailed process for managing emergent work tasks, including asset breakdowns or failures, was included within the scope of the framework. The planning and control of RCA activities was also included – i.e. to ensure that RCA activities are scheduled, to ensure that sufficient resources are made available, and to provide a record when the analysis is complete – but the selection of a specific RCA method or technique was not.

5.3.4. Performance Measurement (AMS component S)

As discussed earlier in section 5.3, the subject of MD includes the capture of data during task execution (e.g. inspection findings, measurements, work history) (Global Forum on Maintenance and Asset Management, 2014). This data, usually captured during WO closure in the CMMS, is a vital input for effective performance measurement (Wulff, 2005; Lorenzi, 2017) – i.e. without access to the necessary data, captured in a format that is easily retrievable and presentable, effective performance measurement cannot take place (Kherun et al., 2002; Duffuaa and Raouf, 2015; Parida et al., 2015). Therefore, in order to ensure that effective performance measurement is possible for the end user of the framework, it was recognised that the framework scope needed to include features that would enable the end user's CMMS to be configured in alignment with their specific performance measurement requirements – i.e. with suitable input fields to capture the source data required for each desired report (Barry and Stevens, 2011; Kumar et al., 2013; Parida et al., 2015). Additionally, it was recognised that the framework scope also needed to include the core elements of a performance measurement process, to ensure that the required data is actually collected in practice as an integrated part of day-to-day maintenance processing.

By combining the thinking of several authors (Kutucuoglu et al., 2001; British Standards Institute, 2007; Barry and Stevens, 2011; Kumar et al., 2013; Parida et al., 2015), the following broad consensus was deduced regarding the core elements of a performance measurement process:

1. Key Performance Indicator (KPI) selection
2. Data collection
3. Reporting
4. Analysis
5. Action to deliver improvement
6. Assessment of the effectiveness of actions taken and sharing of lessons learnt (Institute of Nuclear Power Operations, 2010)

Therefore these steps were integrated into the framework scope, with the exception of step 1 (i.e. the selection of KPIs). Consider that this is a one-off activity that is performed in advance; whereas the planning and control of maintenance activities is a continuous, day-to-day, operational process – there is clearly no scope for merging these activities together into a single process due to the differences in timescale; KPI selection can be done independently in advance. Furthermore, there is already a large body of existing research on the subject of selecting KPIs – many selection frameworks already exist and it was not considered to be a good use of time to develop another specifically for this project (Kutucuoglu et al., 2001; Campbell and Reyes-Picknell, 2006; British Standards Institute, 2007; Parida and Chattopadhyay, 2007; Barry and Stevens, 2011; Simões, Gomes and Yasin, 2011; Kumar et al., 2013; Parida et al., 2015). However, all of the other performance measurement process steps listed above (i.e. steps 2 – 6) are continuous, day-to-day activities and are therefore appropriate for inclusion within the framework scope.

Therefore in summary, the framework scope did not include methods on *how* to select the appropriate KPIs; it was assumed that the end user would already have pre-existing KPI requirements. However, it was recognised that the end user's specific KPI requirements would be different in each case, and therefore the framework would need to be flexible in this regard so that it could adapt to any potential KPI combination. Therefore the framework scope was expanded to include an extensive list of maintenance KPIs (extracted from the literature – see later in section 6.1.3), so that every possible performance measurement requirement could be catered for. Against each optional KPI would be two crucial pieces of information: 1. clearly defined CMMS implementation requirements to enable the relevant fields to be configured for data capture; and 2. the corresponding business process steps needed to ensure that data is actually entered into these fields during maintenance execution.

5.3.5. Continuous Improvement (AMS Component W)

Most authors agree that the purpose of performance measurement is to enable problems to be identified, so that action can be taken to deliver improvement (Parida and Chattopadhyay, 2007; Myeda, Kamaruzzaman and Pitt, 2011; Fernandez and Marquez, 2012; Kumar et al., 2013; Parida et al., 2015). This is the same purpose as an RCA process, as described earlier in section 5.3.3 – i.e. significant or recurring failures are identified and analysed to identify and eliminate the root cause, in order to deliver an improvement in performance (Sharma and Sharma, 2010; Port, Ashun and Callaghan, 2011; Jackson, 2016). Because both processes are routes to the same outcome (i.e. improvement), it was considered most effective to combine them into a common section of the framework, which would focus on delivering improvement. Improvement opportunities would be sourced from both of these areas (plus any other suitable sources that were identified during framework development), and then implemented via a common improvement process.

5.3.6. Maintenance Requirements Analysis (MRA)

This subject involves determining an asset's maintenance requirements, i.e. all of the detailed activities that must be carried out in order to meet business objectives (Global Forum on Maintenance and Asset Management, 2014; British Standards Institute, 2014b). This corresponds to AMS component H in a maintenance-specific life-cycle context (see Fig. 7, section 5.1.1). Because each required activity will be fed into the MD process for planning and execution (usually via the CMMS – or component M as shown in Fig. 7), there was clear justification for including MRA within the scope of the framework at least at a process level, to ensure that this analysis is actually carried out when necessary, and to ensure that all required information is transferred into the CMMS in the correct format. However, the precise methodology for determining maintenance requirements was not included within the framework scope, because as with performance measurement and RCA, MRA is an entire subject in itself (i.e. reliability engineering) and there is already a large body of work on existing techniques such as Reliability Centred Maintenance and Failure Mode and Effects analysis (Nowlan and Heap, 1978; British Standards Institute, 2006; Campbell and Reyes-Picknell, 2006; British Standards Institute, 2010; Peters, 2014; US Department of Defense, 2014) – therefore it was assumed that the end user would define their preferred methodology elsewhere.

5.3.7. Materials Management (MM)

According to the literature, maintenance activities cannot be delivered effectively without a reliable supply of spare parts, therefore there is a substantial interface between the subjects of MD and Materials Management (MM) (Samaranayake and Kiridena, 2012; Peters, 2014; Duffuaa and Raouf, 2015). However, MM is an entire discipline in itself, therefore it was necessary to limit the scope of this research to the parts of MM that have the biggest impact on MD. According to Van der Westhuizen and West (2016), it is the timely retrieval of parts from the storage area and supply to the place of work execution that has the biggest impact – i.e. if the parts withdrawal process is too slow, then this will have a negative effect on the timely execution of work (Samaranayake and Kiridena, 2012; Shafeek, 2014) (this is especially important for maintenance-significant items, i.e. those that can have a critical impact on production if they are unavailable when a demand is placed). Also, the trigger for the withdrawal of parts comes from the materials requirements listed in the WO (Institute of Nuclear Power Operations, 2010; Peters, 2014; Duffuaa and Raouf, 2015) – therefore there is a clear synergy between MM and the CMMS elements of MD that were defined earlier in section 5.3.1. Additionally, according to Van der Westhuizen and West (2016) there has been little research on how to integrate this particular area of MM with MD, therefore including it in this project provided more opportunities for innovation. Therefore in summary, only the retrieval of parts from the storage area and the supply to the place of work were included within the framework scope (from here onwards referred to as "Parts Acquisition"); other areas of MM were not included (i.e. inventory management, stock control, demand forecasting, procurement). It was assumed that the end user's warehouse function would already have existing processes in place for managing stock levels and ensuring sufficient material availability on the shelves.

5.3.8. Shutdown / Turnaround / Outage (STO) Management

Depending on the sector, certain assets may have a significant portion of their maintenance requirements that cannot be executed whilst the asset is operational due to inherent hazards – i.e. they must be shut down in order to carry out such tasks safely; this is referred to as shutdown, turnaround or outage (STO) maintenance (Peters, 2014; Duffuaa and Raouf, 2015). STO maintenance activities differ from normal, operational maintenance in that there is a significant amount of additional logistical planning to do up-front, i.e. to arrange the production stop with key stakeholders such as the production department, customers and distribution etc. (Campbell and Reyes-Picknell, 2006). However, the planning and control of the STO maintenance work itself is no different to normal maintenance, therefore the same MD process can be utilised for both situations – provided that there is a clear way of identifying which tasks require a STO event so that they can be grouped together into a STO work scope (Campbell and Reyes-Picknell, 2006; Institute of Nuclear Power Operations, 2010; Peters, 2014). Therefore, this additional feature was included in the framework scope to ensure that it was suitable for both operational maintenance and STO maintenance. Clearly, this needed to be an optional part of the framework as it will only be relevant in certain contexts (i.e. businesses that require STO maintenance).

5.4. *Conclusion*

In summary, based on a review of the literature, it was determined that the scope of the framework would include the following elements of the subject areas listed below:

- **Information Management (M)** – close alignment of the supporting CMMS software was found to be critical to the success of any MD process. Therefore alongside a tailored business process, the framework was expanded to also produce a fully aligned CMMS implementation specification for the end user, which is also tailored according to the same contextual requirements. This will enable the end user of the framework to not only create a tailored MD process, but also to ensure that they are able to purchase, implement and configure a CMMS that has the necessary capabilities to fully support that process.
- **Outsourcing (R)** – the planning and control of outsourced labour was included in the framework scope, alongside insourced labour. However, the commercial aspects of outsourcing, such as the agreement of service contracts and supply arrangements, was excluded.
- **Performance Measurement (S)** – performance measurement was included in the "Improvement" section of the framework at a process level. An extensive list of optional KPIs was also included so that the end user could select their pre-existing KPI requirements. Against each of these optional KPIs would be clearly defined CMMS implementation requirements to enable the relevant fields to be configured for data capture, plus details of the corresponding business process steps needed to ensure that data is actually entered into those fields during maintenance execution.

- **Failure Management (V)** – the management of corrective actions in the event of failure ("Emergent Work") was included in the framework scope, via its own section. The execution of RCA investigations was included in the "Improvement" section of the framework at a process level, alongside performance measurement; however, the specification of a precise RCA methodology was excluded.
- **Continuous Improvement (W)** – as stated above, both the RCA and performance measurement processes were combined into a common improvement process, which would consider improvement opportunities from a variety of sources, and manage the execution of improvement initiatives.
- **Maintenance Requirements Analysis** – MRA was included within the scope of the framework at a process level, to ensure that it is carried out and that all outputs are transferred into the CMMS in the correct format. However, the specification of a precise MRA methodology was excluded.
- **Materials Management** – parts retrieval and supply to the place of work execution was included within the framework scope; other MM processes such as inventory management and procurement were excluded.
- **STO Management** – the planning and control of STO maintenance activities was included within the framework scope, via the addition of a STO work identifier. The management of up-front, logistical STO activities was excluded.

This piece of work enabled the completion of RO 1, as defined in section 5.1.6. The completion of RO 2 will be documented in the next section of this report (section 6) – i.e. the development of a preliminary version of the framework (i.e. Framework v1) via a review of all existing MD practices from the literature that fell within the defined scope.

5.4.1. Innovations

The diagram shown in Fig. 7 (see section 5.1.1), which illustrates the relationships and dependencies between the 23 AMS components (as defined in the codebook from section 3), is both useful and novel. It perfectly supplements the codebook, which was already claimed previously as an innovative AMS assessment tool, by providing a clear overview of all elements of the AMS. Used alongside the codebook, this makes the assessment or development of an ISO-aligned AMS even easier. The diagram is also very useful for explaining the concepts of an AMS in a simple, 1-page format, which is ideal for training and raising awareness of AM (which is something that organisations need to do in order to comply with clause 7.3 of ISO 55001 (British Standards Institute, 2014b)). The author has already used it in this manner to great effect within the sponsor organisation (Catt, 2015b; 2015c; 2017), and plans to publish a paper at a later date describing its development and use.

The main deliverable of this research project – i.e. the tailorable framework of practices for MD (the development of which will be described later in this report) – is innovative in several ways due to the nature of its scope and boundaries:

1. It covers multiple AM subject areas that are not normally combined, via a single, holistic solution that takes the subject of MD beyond its existing boundaries. i.e.:
    - the planning and control of maintenance activities
    - the configuration and implementation of supporting CMMS software
    - the utilisation of outsourced labour to deliver maintenance
    - the measurement of maintenance performance
    - the management of corrective actions in the event of failure
    - the root cause analysis of failures to drive improvement
    - the collation of improvement opportunities and the execution of improvement initiatives
    - the determination of maintenance requirements via analytical methods
    - parts acquisition and supply to the point of use
    - The execution of STO activities.

2. The ability of the framework to generate a fully aligned implementation specification for the supporting CMMS, which is also tailored according to the same contextual requirements – is also innovative, as it combines a tailored business process design tool with a software specification tool to solve a common industry problem (i.e. poor alignment between the MD process and the supporting CMMS). This will enable the end user of the framework to not only create a tailored MD process, but it will also ensure that they are able to purchase, implement and configure a CMMS that has the necessary capabilities to fully support that process.

3. The framework is not only useful for the sponsor of this research, it can be used by any business that plans and controls maintenance activities. It contains options from multiple different industries and sectors, enabling the end user to consider practices from a wide range of sources in order to develop an effective MD process to suit any

context. A generic, universal framework that can be useful in many different industries is unique, because existing MD processes are generally designed for a single, specific case and do not take into account different contexts; therefore, by developing such a framework, this research has demonstrated innovation and made a useful contribution to the wider AM field.

6. A Literature-based Preliminary Solution

This section will describe the work undertaken to address RO 2, as defined in section 5.1.6. A preliminary version of the framework (i.e. Framework v1) was developed via a systematic review of all existing MD practices from the literature that fell within the defined scope from section 5.3.

6.1. *Methodology*

The literature was exhaustively searched for any sources that described processes or practices for MD within the framework scope, as defined above in section 5.3. Each source was qualitatively analysed via a hierarchical descriptive coding process, to extract each practice and summarise its content (Saldaña, 2011; 2014; Tracy, 2013; Yin, 2015). These practices were built up into a comprehensive list or codebook (Tracy, 2013), containing all possible practices from all available sources in the literature (see Appendix C). The same coding methodology that was utilised in section 3.1 was used again, with the following exceptions:

- Rather than looking for AMS requirements, the aim was to identify and summarise MD practices within the defined scope of the framework. As in section 3.1, codes were categorised via a hierarchical structure, based on their subject area (e.g. maintenance planning, emergent work processing), in order to identify suitable sub-sections for the framework.
- The qualitative data analysis software package "NVivo"[1] was used, rather than the manual paper-based coding system that was used previously in section 3.1. This was due to the greater number of sources and the larger source size, which made paper copies impractical.

Once a complete list of MD practices was defined, they were mapped out via a series of flowcharts to show the relationships between practices, which were deduced based on their inputs and outputs as described in the literature. Practices were represented by process step blocks, and the relationships between them were shown via directional arrows. As a result of this approach, the completed framework resembles a business process diagram, with the exception that it contains many optional steps that the end user can select between in order

[1] For further information see: http://www.qsrinternational.com/what-is-nvivo

to design their own tailored business process. Optional steps were established whenever differences or conflicts were found in the literature (for example between different industries or sectors). Guidance on the pros and cons for each option were included to facilitate decision making, where available in the literature. A series of tables accompanies the flowcharts, in order to present clear definitions, justifications and references for each process step. The final version of the framework can be found in Appendix D for reference.

6.1.1. Literature Search Parameters

Initial search terms comprised of combinations of the words: "Maintenance Delivery process", "Maintenance planning and control process", and each of the "in-scope" subject areas listed earlier in section 5.3. These initial search terms were expanded as further appropriate terminology was discovered during the searching process. Whenever new terminology was identified, the process was repeated so that through iteration the widest possible range of sources was reached. A complete list of search terms is shown below:

- Maintenance Delivery process
- Maintenance planning and control process
- Maintenance business process
- Maintenance Work Order process
- Maintenance Work management system
- Maintenance planning system
- Maintenance management
- Maintenance scheduling
- Maintenance Information Management
- Computerised Maintenance Management System
- Maintenance Performance measurement
- Maintenance Key Performance Indicators
- Maintenance Root cause analysis
- Root Cause Failure Analysis
- Maintenance Continuous Improvement
- Maintenance Improvement Process
- Maintenance Outsourcing Process
- Maintenance Requirements Analysis
- Maintenance Materials Management

- Shutdown / Turnaround / Outage Maintenance

The following sources were searched, based on the resources available to the author as a University of Warwick student:

- The University of Warwick Library.
- All database subscriptions listed under "Manufacturing" and "Engineering" on the University of Warwick library website. Examples include ProQuest, Emerald Insight and OECD iLibrary.
- Scopus – the largest database of peer-reviewed literature (Scopus, 2019).

6.1.2. Acceptance Criteria

For literature to be accepted for review, it had to describe processes or practices for MD within the defined scope of the framework, being either:

- generic practices that could work in multiple contexts;
- specific practices designed for a single context;

Note that practices from any industry or sector were considered, as long as the activities being managed were maintenance. Sources were accepted whether they covered a broad or narrow range of the full framework scope, e.g. from complete end-to-end business processes to single, discrete practices.

6.1.3. The KPI section of the framework

In section 5.3.4, it was determined that the core elements of a performance measurement process would be included within the framework scope – with the exception of the *selection* of KPIs. This is because KPI selection is a one-off, up-front activity that cannot feasibly be integrated into a continuous day-to-day process like MD (in addition, numerous KPI selection frameworks are already available in the literature). Therefore it was decided that the framework would offer no guidance on how to select appropriate performance measures; it would assume that the end user already had pre-existing KPI requirements in place. However, it was recognised that in order for effective performance measurement to be possible, the end user's CMMS must be configured in alignment with their specific KPI requirements – i.e. with suitable input fields to capture the source data required for each report. And because the end user's specific KPI requirements will be different in each case, it was recognised that the framework would need to be flexible enough to adapt to any potential KPI combination, and provide a fully compatible CMMS implementation specification for any case. Additionally, for certain KPIs, it was recognised that specific business process steps are required to ensure that the required data is actually collected in practice as an integrated part of day-to-day maintenance processing – and therefore the framework would also need to take this into account.

Therefore an extensive list of possible maintenance KPIs was extracted from the literature and included in the framework, complete with a thorough definition and a list of references for each KPI (see Appendix D for a complete list). CMMS implementation requirements were developed for each KPI, specifying the input fields required for data capture. Additionally, against each KPI was a list of the mandatory business process steps that are required to ensure that the relevant data can be collected in practice. This will allow the end user of the framework to locate their own pre-existing KPIs from the list, and understand the impact that this will have on their tailoring options within the framework. Consequently, it was recognised that this KPI selection feature would need to be one of the first phases of the tailoring process (because KPI choices influence the rest of the framework design), therefore it was located in a prefix section of the framework.

The format for the configuration specification for KPIs is presented as follows:

> [CMMS Component, Subset of Component] Name of Subset (= Property of Subset*)
> (*where applicable; not all subsets require specific properties)

For example:

> [WO, Field] WO Type = Routine
> [Asset Record, Field] Asset Criticality = Critical
> [WO Request, Status] Complete
> [Asset Record, Function] Ability to flag fields as mandatory

6.2. *Results – Framework v1*

81 sources were found in the literature that met the acceptance criteria defined in section 6.1.2 (i.e. literature describing processes or practices for MD within the defined scope of the framework). They came from a variety of different sectors including infrastructure, facilities management (FM), utilities, oil and gas, paper, cement, healthcare, military, aviation, naval, nuclear and chemical. Each source was analysed and coded to determine all possible MD practices present in the literature (a complete list of these codes, cross-referenced with their sources, can be found in Appendix C). Each practice was then sequenced and mapped out into a series of process flowcharts to provide a visual overview of the framework (as defined in the methodology in section 6.1), and these flowcharts were accompanied by a series of tables presenting clear definitions, justifications and references for each process step. All optional practices were clearly highlighted, and guidance for selecting the appropriate options based on the context was also provided. The findings on possible KPI requirements were also incorporated into the framework as a prefix section, as discussed in the methodology in section 6.1.3. Additionally, a list of essential CMMS functionality was also developed from the literature, which defines universal CMMS requirements that are necessary in all contexts, independent of process tailoring. This list was also incorporated into the prefix section of the framework.

Only a high-level overview of Framework v1 will be presented in this report, because it is only considered to be a preliminary version (Framework v2 is presented in full in Appendix D). An overview of the main sub-sections of Framework v1 is shown below in Fig. 8. These sub-sections, which were developed by categorising the codebook into a hierarchical structure (as per the methodology in section 6.1), can be summarised as follows:

1. **Asset Register** – includes new asset installation / existing asset modification; assets are registered in the CMMS with all required data and are categorised appropriately; assets are decommissioned at end of service and CMMS data is archived.
2. **Routine Maintenance Requirements** – maintenance requirements are identified and routines are registered in the CMMS, with a defined scope of work, due date and frequency.
3. **Emergent Work Request and Screening** – asset breakdowns / defects are identified and corrective maintenance is formally requested. Each request is reviewed,

screened (i.e. approved / rejected), prioritised according to urgency, and then assigned to a planner for resolution. High priority / emergency tasks are processed differently to achieve faster resolution times.

4. **Planning** – a safe and effective execution method is determined for each task; tasks are broken down into discrete steps with defined durations and manning requirements; all required resources are determined (i.e. parts, tools, access); materials are sourced and staged ready for execution.
5. **Scheduling** – execution dates are optimised according to resource availability, task urgency, and production requirements; work assignments are allocated for individual maintenance technicians.
6. **Execution** – tasks are safely executed, reviewed and recorded as complete in the CMMS; data is captured for failure analysis and performance measurement.
7. **Improvement** – performance data is collected and analysed to identify opportunities for improvement; significant or recurring failures are analysed to determine the root cause; improvements from both sources are collated, assessed for cost / benefit, actioned to deliver improvement, and reviewed to quantify the benefits realised.

Note that the full Materials Management process is not within the framework scope (as discussed in section 5.3.7), but is shown on the diagram for reference.

A Tailorable Framework of Practices for Maintenance Delivery – Overview

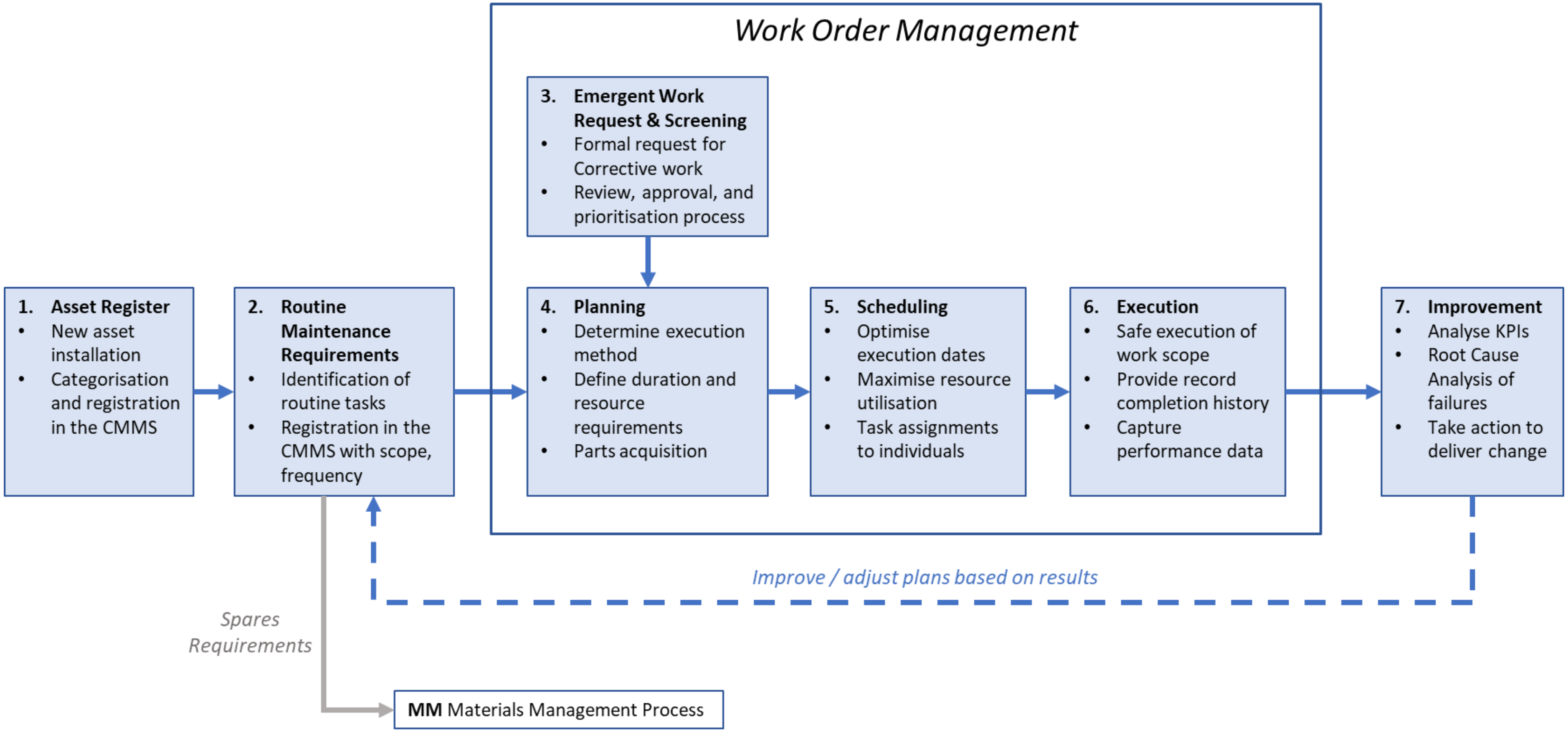


Fig. 8 – An overview of the main sub-sections of Framework v1

6.3. *Conclusion*

Version 1 of the framework was successfully developed via the synthesis of 81 different sources from the literature (see Appendix C). Their content was coded, analysed and combined to develop a comprehensive framework covering all possible MD practices present in the literature. Options were identified whenever multiple conflicting practices were encountered (e.g. from different industries or sectors), and guidance on selecting the most appropriate option for a given context was included where available, to enable the end user of the framework to develop their own tailored business process. A detailed CMMS implementation specification was also developed for each process step, enabling the end user to implement and configure their CMMS in full alignment with their tailored business process. The format for the configuration specification is as follows:

> [CMMS Component, Subset of Component] Name of Subset (= Property of Subset*)
> (*where applicable; not all subsets require specific properties)

A series of typical examples are presented below to illustrate this format:

> [WO, Field] WO Type = Routine
> [Asset Record, Field] Asset Criticality = Critical
> [WO Request, Status] Complete
> [Asset Record, Function] Ability to flag fields as mandatory

The framework includes a specification of this nature for each process step requiring CMMS support, totalling 133 individual specifications in version 1 of the framework. This piece of work completed Research Objective (RO) 2 as defined in section 5.1.6.

6.3.1. Limitations

Regarding RO 2c (i.e.: *"Ensure that each optional practice is accompanied by appropriate guidance to facilitate decision making"* – see section 5.1.6): unfortunately, only limited guidance on the pros and cons for each optional practice was available in the literature, because each text that was reviewed typically only presented a single viewpoint (i.e. the author's preferred view), that described how MD is practiced in a specific context without clear justification or explanation as to why. Consequently, this guidance information had to be found elsewhere; therefore RO 2c was moved into RO 3, to be discussed with industry experts during the development of Framework v2.

6.3.2. Innovations

Framework v1 contained numerous practices that were not sourced from the literature, but were instead added directly by the author. These were referred to as “red practices” (because they were highlighted in red colour in Framework v1), with the following definition:

- Any MD practice that does not have a reference from the literature.

Each red practice was added for one of two reasons:

A. They were known to be practiced in industry, based on the author’s experience of a decade working in the MD field. However, despite searching extensively across numerous sources, references could not be found in the literature.
B. They were potential innovations – i.e. new ideas that were conceived by the author during the development of the framework, that in the author’s view improved upon the content found in the literature, and went beyond the current practices found in industry.

Each “red practice” was discussed with multiple industry experts (the criteria for selecting “experts” is defined in section 7.2) during the development of Framework v2, to determine if they fell into category A or B above (see section 7.4.2 later). It was recognised that if at least 1 expert could verify that the practice was genuinely carried out in industry today, then it would fall into category A. Any such findings would demonstrate that there are practices carried out in industry that are not commonly documented in the literature, enabling this research to add to the body of knowledge.

If, after interviewing multiple experts, none could be found to verify the presence of a particular “red practice” in industry, then this practice would fall into category B – i.e. a potential innovation. This would mean that the practice is novel to both the literature and to industry – however, to be classed as innovative it was recognised that the practice must not only be novel, but also non-trivial and beneficial (Berkun, 2013). Therefore, each expert was also asked if the “red practice” was a positive addition to the framework that would make a significant improvement to MD performance in their context. If this was also the case, then it would be classed as an innovation.

A summary of potentially innovative “red practices” that were likely to fall into category B are shown below in Table 4, with reasons given in each case:

Framework Step	**Details of potentially innovative practice**
1.09 Modify Asset Record in the event of a change	The use of the CMMS to log formal requests for changes to Asset Data, and to provide a record of such changes, is potentially innovative. This is normally done via a paper form system, and would be more robust and time-efficient if recorded via a specific WO Request in the CMMS.
3.10 Send feedback to requester automatically	The use of the CMMS to automatically inform the requester that their proposal has been rejected, and to explain why (to ensure that the user is not discouraged from reporting defects in the future) is potentially innovative. This would normally be done in an informal, ad-hoc manner – if at all. An automatic, email response will ensure that the feedback is delivered promptly every time.
4.10 Define scheduling constraints	The use of a specific CMMS field during planning to define any constraints that will influence WO scheduled start dates, is potentially innovative. This will improve the communication between planner and scheduler, which is often informal and unreliable and results in scheduling errors.
5.07 Formal request for deferral	The use of the CMMS to log formal requests for due date extensions, and to manage the deferral process, is potentially innovative. This is normally done via a paper form system, and would be more robust and time-efficient if recorded via a specific WO Request in the CMMS.
5.10 Change WO Status = "Scheduled (Proposed)"	The use of a specific WO Status to show that MT scheduling is complete and ST scheduling is required, is potentially innovative. Normally there is no clear identifier in the CMMS between these key process stages, which if present would improve workflow efficiency.
6.28 Confirm Actual Duration (Delay Codes)	The use of the CMMS to capture the reasons for any execution delays via specific Delay Codes, is potentially innovative. Whilst execution delays (in hours) are commonly recorded in the CMMS, the reason for each delay is not. Doing so would enable this data to be trended to reveal the biggest cumulative causes of delay, to identify opportunities for improvement.

Framework Step	Details of potentially innovative practice
7.06 Create WO Request (Type = Improvement)	The use of the CMMS to log improvement suggestions and to manage improvement activities is potentially innovative. Improvement suggestions are normally logged in a separate system (if at all) – but since improvement activities often utilise maintenance resources, it would be better to fully integrate them into the CMMS, so that they can be screened, planned, scheduled and executed alongside normal maintenance tasks.

Table 4 – Summary of framework steps containing potential innovations

Other innovations from this section include the construction of the framework itself, i.e. the synthesis of many different MD practices from various sources, to create a generic, universal model that can be tailored to suit any context. The framework is also very wide-ranging and holistic in that it covers several interlinked – but normally separate – AMS components into a single holistic package. The ability of the framework to generate a fully aligned implementation specification for the supporting CMMS, which is also tailored according to the same contextual requirements – is also innovative, as it combines a tailored business process design tool with a software specification tool to solve a common industry problem (i.e. poor alignment between the MD process and the supporting CMMS). This will enable the end user of the framework to not only create a tailored MD process, but also ensure that they are able to purchase, implement and configure a CMMS that has the necessary capabilities to fully support that process.

7. Confirmation and Improvement of Initial Framework Design via Expert Elicitation

This section will describe the work undertaken to address RO 3, as defined in section 5.1.6. Expert opinion from industry was utilised to validate and improve upon the initial literature-based framework design. Specifically, there were three issues with Framework v1 that needed to be addressed:

1. The first issue was defined in Research Objective (RO) 3a (see section 5.1.6 for a full definition of all ROs), i.e.: "*Revise any missing or incorrect practices to ensure that the framework is fully comprehensive and able to produce an effective MD process in any context.*" Framework v1 was based predominantly on the literature (with the exception of several "red practices" that were added based on the author's experience – see issue 3 below), and although it was developed from a large number of sources, it was anticipated that there may have been additional practices utilised in industry that were not present in the literature. There could also have been some mistakes or misinterpretations present that would invalidate the initial version of the framework; the aim was to discover these in order to make the framework as robust and comprehensive as possible.

2. Framework v1 included several optional practices to enable the end user to develop their own tailored MD process based on their context. However, one of its limitations (as discussed earlier in section 6.3.1) was that a full range of contextual guidance for each optional practice was not available in the literature, therefore this issue had to be addressed by utilising guidance from industry experts instead.

3. As discussed in earlier in section 6.3.2, Framework v1 included several "red practices" that were added directly by the author – without references to the literature – which could have been either: (A) new knowledge that was practiced in industry but was not recorded in the literature, or (B) innovations that were conceived by the author during the development of Framework v1, that improved upon the content found in the literature and went beyond the current practices found in industry. Each "red practice" needed to be discussed with multiple industry experts in order to make this distinction.

7.1. *Methodology*

A methodology was required to address the three issues raised above, by utilising the opinions of multiple experts from industry. A technique was needed to extract these opinions, analyse them, and manage any disagreements that arose in order to achieve some level of group consensus.

7.1.1. Selection of Research Approach

The Delphi method is considered to be the most common and well-proven technique for eliciting and analysing expert opinion (Erffmeyer et al., 1986; Mullen, 2003; Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009; Marchau and Van de Linde, 2016); therefore it was selected for use in this study. Delphi is traditionally a forecasting technique that utilises a series of questionnaires, but it has evolved in recent years into more general use, which can take other formats including interviews – as long as the following set of key principles are adhered to:

- Participants are consulted for their opinions in a series of rounds, with controlled feedback in between;
- This feedback consists of a summary of their opinion in comparison to the group average (therefore some level of statistical quantification is required). This encourages any outliers to adjust their views in order to align with the wider community, or else justify their differences. It is therefore an iterative process whereby consensus draws closer as the rounds progress and opinions align;
- The participant's responses are anonymous, i.e. they do not interact with each other directly. This removes any source of influence from dominant figures, allowing unusual or unpopular opinions to surface freely

  (Erffmeyer et al., 1986; Mullen, 2003; Okoli and Pawlowski, 2004; Miller, 2006; Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009; Ononiwu, 2013; Marchau and Van de Linde, 2016).

Consider that the Delphi technique is suitably aligned with the aims of RO 3 for the following reasons: it is a practical method for eliciting opinions from a diverse group of experts because they don't actually have to meet each other or be in the same place at the same time (e.g. like in a focus group – which would be logistically very difficult to achieve with industry experts from different organisations in different countries with inevitably busy schedules); the structured, round-based approach is also ideal for taking potentially vague initial opinions and transforming them by iteration into clear and valid arguments; and the anonymity principle effectively removes any bias or outside influence, enabling unconventional maintenance practices from atypical contexts to emerge freely. However, it was recognised that one aspect of the Delphi principles listed above would not fit well with the aims of this research, and that was the goal of gradually changing participant's opinions towards the group average in order to converge on a single group consensus. Remember that the central purpose of the framework developed by this research is to present a range of optional MD practices from different contexts, so that the end user can select and tailor their own business process. If the Delphi principle of achieving absolute consensus was followed to its conclusion, then this variety of contextual practices would be lost. Rather than gradually eliminating outlying opinions, the goal in the case of this research was in fact to encourage different opinions to be raised – and justified – so that they could be presented in the framework with clear reasoning and guidance so that the end user can make informed decisions.

Therefore a *modified* Delphi approach was utilised for this research whereby the principle of converging on a group consensus was omitted. The emphasis was instead placed on the deliberate discovery of alternative practices from many different contexts, and on obtaining clear justification for these differing practices. The aim was to deliver maximum improvement to the framework via the addition of further contextual options, complete with effective guidance for tailoring.

7.1.2. Format for the Initial Delphi Round

A common approach in Delphi studies is for the first round to have a different format to the subsequent rounds, with open-ended questions asked in order to gather information – to enable more specific questions to be constructed for the later rounds (Mullen, 2003; Okoli and Pawlowski, 2004; Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009; Ononiwu, 2013). In the case of this research, this approach was highly applicable due to the open-ended nature of the 3 issues raised earlier in section 7. Consider that if these issues were posed as questions – for example for issue 1: "*Do you think that there are there any missing or incorrect practices in this framework*" – the participant's responses would likely focus on very specific details of the framework that could not be pre-determined, and would therefore require follow up questions in order to gain a full understanding their opinion (e.g.

What would you do differently on your site? Why is this important in your context?). Clearly there was the need for an open, in-depth discussion on how MD was implemented at each expert's site, to compare the framework to their own practices and to examine the differences. The nature of such open-ended discussion meant that data gathering by interview was clearly the most appropriate technique for round 1, as this would allow the direction of questioning to adapt based on the responses of the interviewee (Tracy, 2013; Magnusson and Marecek, 2015). If a questionnaire format was utilised instead for these initial questions, it would have been highly impractical due to the large number of process steps contained in the framework and the multitude of possible responses and follow up questions. There would simply have been too many questions, which would have been tedious for the participants to complete, leading to a low response rate – the aim was to strike a balance whereby sufficient data could be obtained to draw a conclusion, without requiring an unreasonable amount of effort from the participants (Schmidt, 1997). It was recognised that only a face-to-face interview would allow for the in-depth, open-ended discussion necessary to elicit the expert's opinion with clarity, without taking up too much of their time.

An added advantage of a face-to-face interview was that there would be time to explain the research background and goals in person – this was considered important for getting the interviewee invested in the outcome in order to improve the quality of the responses (Marchau and Van de Linde, 2016). And because the framework was quite large and detailed, an interview would also allow participants to ask any questions or request clarifications if certain aspects of the framework were not clear to them. This approach allowed for example several formatting and layout issues to be raised, recorded and utilised later to improve Framework v2.

The main disadvantage of an interview approach was that it was more time consuming for the researcher (when compared to a questionnaire), due to the amount of time required to conduct each interview and to travel to the participant's locations. This undoubtedly reduced the total number of experts that could be approached in the time available; however, due to the improvement in the quality and depth of responses, this was considered to be a worthwhile trade-off. It was also recognised that in an interview context, studies have shown that researchers are able to subtly influence participant's responses and thus the research outcomes (Mullen, 2003; Hsu and Sandford, 2007; Aichholzer, 2009; Marchau and Van de

Linde, 2016) – therefore the principal of impartial and unbiased questioning was adopted throughout the interview process.

The Round 1 interviews utilised an informal style with a series of open-ended questions, broadly in alignment with the three issues raised at the beginning of section 7. Consider that the open-ended nature of these questions meant that there could have been many possible responses, and therefore it was necessary to analyse each participant's responses via a descriptive coding process. It was recognised that two participants could make the same suggestion, but phrase it completely differently – therefore coding was needed to determine if their opinions truly aligned or differed in order to prevent any data duplication that could compromise the results (Ononiwu, 2013). Coding also enabled each participant's opinions to be concisely summarised to facilitate the analysis of the data (see section 7.4.2). The same descriptive coding technique that was utilised earlier in section 3.1 was used again – as derived from Saldaña (2011; 2014), Tracy (2013) and Yin (2015) – with the exception that rather than looking for AMS requirements it looked for expert's opinions and suggestions regarding Framework v1.

7.1.3. Format and Quantity of Subsequent Delphi Rounds

Recall that the objective of this research was to identify additional MD practices from industry, and to obtain guidance on the contexts in which it is beneficial to implement these practices. Consider that any given practice could either be beneficial in all contexts (and therefore should become a mandatory part of the framework), or in a small number of specific contexts (and therefore should only be added as an optional practice). In order to make this distinction, it was necessary to elicit an opinion on every practice from every participant, in order to assess the practice's usefulness in as many different contexts as possible.

Therefore with regards to the subsequent Delphi rounds – it was recognised that after the initial interview stage was completed and all responses had been analysed, it was likely that many additional practices would have been suggested by the participants. However, each of these practices would have come from a single participant during their interview, and would not have been discussed with any of the other participants – i.e. their opinion on the usefulness of that particular practice in their context would have been unknown. Therefore to resolve this issue, the aim of all subsequent Delphi rounds was to take any new practices suggested in the previous round, and relay them to each participant to determine if it was appropriate or not in their context. This was necessary to determine if each new practice should become a mandatory or optional part of the framework – and if it was optional, to develop appropriate contextual guidance (i.e. in line with issue 2 in section 7).

Considering now the format for the subsequent rounds: it was recognised that an interview format would not be practical because it would be too time consuming for the researcher, and for the participants, to return to every participant for a second (or third or fourth) time for further face-to-face discussion. A self-complete style questionnaire was considered to be the more appropriate choice because this could be delivered simultaneously and electronically to each participant to save time (Okoli and Pawlowski, 2004; Ononiwu, 2013). At this stage in the Delphi process, all of the open-ended, in-depth discussion would have already taken place (i.e. in the first round), and only specific, closed questions would remain – which are ideally suited to a questionnaire format (Brace, 2013; Saris and Gallhofer, 2014). It was also anticipated that questionnaire response rates would be favourable because each participant would already have taken part in the "face-to-face" initial round, and would hopefully have built up a rapport with the researcher and have some level of personal investment in the research outcomes.

It was recognised that questionnaire length was an important factor in achieving a favourable response rate (Schmidt, 1997) – therefore a limit of 24-36 questions was set based on recommendations from Graham (2008). Too many questions in round 2 would risk demanding too much from the participants, resulting in a lower response rate (Schmidt, 1997). Therefore, a prioritisation process was developed to determine which of the round 1 suggestions should go forward to round 2 for further scrutiny; the detailed prioritisation mechanisms that were employed are shown below in Table 7. It was recognised that each prioritisation mechanism would introduce risk with respect to the integrity of the conclusions drawn from this research – therefore these risks were assessed and actions were taken to mitigate them (also as described below in Table 7).

	Prioritisation Mechanism	Risk	Mitigation / Reason risk is acceptable
A	If a suggestion only adds an additional option to the framework, without taking away or contradicting any existing content, then the suggestion will be accepted without round 2 involvement (as an additional option only).	The additional option could be “bad” practice, suggested by an inexperienced participant. It has not been reviewed or verified by all participants.	Each participant has been carefully selected with a minimum experience threshold, therefore the likelihood of poor suggestions due to a lack of experience is low. The additional practice will be completely optional and all existing practices from Framework v1 will still be present in Framework v2 – so if poor optional practices are inadvertently added, they can simply be ignored by the end user. The target end user of the framework will be an experienced MD professional, therefore they will be capable of recognising bad practices and not selecting them during tailoring.
		The additional option is not applicable in certain contexts.	The framework is intended to give various options for multiple different contexts. The addition will be clearly labelled as a contextual option within the framework, alongside the original content. Guidance will be included to explain when it is appropriate to select this option (based on the comments obtained from the source participant during round 1).
B	Any comments that were coded as “guidance” will be accepted and added to Framework v2 without round 2 involvement.	Missed opportunity to present the idea to the other participants, to provoke more thinking and produce additional guidance or practices	It was anticipated that guidance comments could not be included in round 2, as this would result in a questionnaire with too many questions, which would risk demanding too much from the participants, resulting in a lower response rate. It was recognised that responses regarding suggested changes to the framework need to take priority over guidance suggestions.

		Guidance with few sources may be “bad” guidance.	Each participant has been carefully selected with a minimum experience threshold, therefore the likelihood of poor suggestions due to a lack of experience is low. All comments will be clearly phrased and labelled as advisory guidance only, i.e. they will not be a mandatory part of the framework – therefore end-users can always choose to ignore the advice if they disagree with it. The target end user of the framework will be an experienced MD professional, therefore they will be capable of recognising bad practices and not selecting them during tailoring. Most guidance comments only confirm or state approval for something already in the framework, and therefore just provide an additional source to back up existing content. Any guidance which provides some insight or experience to assist with the selection of optional practices will be written in a balanced manner, with comments both for and against (where available) so that the user can make an informed choice.
C	Suggestions which only expand on existing content to provide more detail, without altering the core meaning, will be accepted without round 2 involvement (e.g. additional CMMS functionality required to support an existing framework step).	The expansion could in fact alter the meaning of the existing content in some unforeseen way.	The original content text will be retained, and the expanded content will only be added in support of it. This expanded content will also be highlighted as advisory / guidance, so that the end user can consider it as an option, rather than as mandatory.

Table 5 – Prioritisation mechanisms used to determine round 2 questionnaire content

For the Round 2 questionnaire, each expert's opinion was elicited via a scoring scale – i.e. with various grades of agreement and disagreement (e.g. "strongly agree" to "strongly disagree") – as is common practice in Delphi studies (Mullen, 2003; Aichholzer, 2009; Marchau and Van de Linde, 2016). As well as providing participants with a clear range of response options, this approach is usually necessary to enable opinions to be quantified so that a group average can be calculated (Mullen, 2003; Aichholzer, 2009; Marchau and Van de Linde, 2016). However, recall from section 7.1.1 that the usual purpose of a Delphi study is to use this group average to gradually change participant's opinions in order to achieve group consensus – but in the case of this research this particular Delphi principle had been omitted. The purpose of this study was instead to identify new practices, and to judge whether or not they should be mandatory or optional (and to elicit guidance on the contexts in which they may be beneficial). Therefore in the context of this study, a quantitative average was not necessary – and it could in fact have been detrimental. Consider that if there were two opposing options in the framework that were "the norm" in different contexts, with strong opinions present on both sides – if an average (i.e. mean) opinion was calculated, this could have potentially resulted in a neutral "neither agree nor disagree" type result, known as a "false consensus" (Mullen, 2003; Hsu and Sandford, 2007). It was recognised that it would be better to just observe the spread of opinion from the different contexts involved, in order to draw a conclusion on the mandatory / optional nature of each additional practice. Therefore the post-interview analysis was conducted as follows: If all participants generally agreed with a suggestion and there were zero "disagree" responses (even "slightly disagree"), then it was accepted and included in Framework v2 as a mandatory practice. If all participants generally disagreed with a suggestion, and there were zero "agree" responses, then the suggestion was not included in Framework v2 (i.e. it was be rejected). If there was a mix of agree / disagree responses, then the practice was added as an option. Guidance on the contexts in which this option should be selected were based on the contexts of the participants that agreed with the suggestion, supplemented by any relevant comments received. In order to elicit such comments, participants were asked to provide reasons for their opinions so that contextual guidance could be constructed. This was achieved via an open comments box at the end of each question section (which were grouped by framework section), to allow participants to elaborate and justify their views.

The question then arose as to how many rounds of iteration would be required in total before the study should be stopped. Most authors agree that the goal in a Delphi study is to reach stability, i.e. when there is little or no change in opinion between rounds (Erffmeyer et al., 1986; Mullen, 2003; Hsu and Sandford, 2007; Marchau and Van de Linde, 2016). However, in the context of this research, where the aim of subsequent rounds was not to change opinion as in a typical Delphi study, but rather to identify additional opinions, it was recognised that the logical “stability” criteria instead needed to be the point at which no further additional practices or changes to the framework were suggested. No definitive answer could be found in the literature as to how many rounds would be required to reach stability, as this is different in each case; sometimes 1 round is sufficient (Skulmoski et al., 2007), sometimes as many as 10 are required (Marchau and Van de Linde, 2016) – however most authors agree that 2 or 3 rounds are sufficient in the majority of Delphi cases (Erffmeyer et al., 1986; Mullen, 2003; Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009; Ononiwu, 2013).

Therefore for this study, it was determined that the 1st round would be an interview to allow for an open-ended discussion to identify additional optional practices from each participant. Further rounds would be questionnaire based, to enable specific follow-up questions to be asked to ensure that opinions were obtained from all participants regarding all additional practices. The total quantity of rounds was initially unknown, but it was determined that further rounds should cease whenever participant’s questionnaire feedback did not include any additional suggestions or changes to the framework.

7.2. *The Selection and Recruitment of Participants*

The selection of participants is considered to be one of the most important issues in a Delphi study – the quality of the experts involved directly influences the quality of the results (Okoli and Pawlowski, 2004; Hsu and Sandford, 2007; Skulmoski et al., 2007; Marchau and Van de Linde, 2016). No clear definition of “expert” could be found in the literature; however for a Delphi study, the following two qualities are considered necessary for all participants:

- They must have suitable background and experience, i.e. be subject leaders, authors of relevant publications, or professionals with first-hand experience of the topic (Mullen, 2003; Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009).
- They must be capable and willing to participate, in terms of availability and communication skills (Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009).

7.2.1. Selection Criteria for Participants

"Suitable background and experience" required defining in the context of this research. It had already been established that an industry viewpoint was needed, rather than an academic one – because this had already been provided via the literature review during the development of Framework v1 (see section 6). What was needed was an understanding of existing practices, as used in industry – to determine if there were any useful techniques that could be added to the framework, and to obtain some confirmation that the framework could actually be useful in the real world. Participants therefore needed to be from industry, with a job role that had responsibility for MD (either a current or previous position), and they must have held that position for long enough to be capable of explaining and demonstrating the MD practices used in their business. They also needed to understand the advantages / disadvantages of their processes, and be able to judge whether the framework would be beneficial in their context or not. It was recognised that these attributes would be present in anyone who held a management / senior planning role with a responsibility for MD.

The participant also needed to work in a relevant industry sector. Only sectors which typically have very intensive maintenance demands were considered (these are often referred to as "asset-intensive" industries):

- Chemical
- Utilities
- Oil and gas
- Power generation
- Energy
- Mining
- Infrastructure

(Lloyd's Register, 2008; Tovstiga, 2013; Edwards and Costa, 2014; Sarno Severi, 2014).

This was on the basis that in these environments, maintenance professionals have to deliver more complex and intensive maintenance programmes – and therefore are more likely to utilise the most effective practices available.

In summary, the following definition was used to specify what "suitable background and experience" meant in the context of this research:

- An industry professional with at least 10 years' experience
- In a senior / management role with responsibility for MD (either a current or previous position)
- From an asset-intensive industry

All potential participants were screened prior to their involvement in this study to ensure that they met the requirements of this definition, according to the judgement of the author.

7.2.2. The Required Quantity of Participants

The required quantity of participants for a Delphi study is not clearly defined in the literature; previous studies range from as low as 3 participants to as many as 171 (Skulmoski et al., 2007), because the required number is highly variable depending on the type of problem being investigated.

Another key factor that can influence the required quantity of participants is the breadth of expertise required: a homogeneous group (i.e. with a single area of expertise) will require fewer participants in order to reach saturation (Hsu and Sandford, 2007; Skulmoski et al., 2007; Aichholzer, 2009). For this study, a homogeneous group of participants was utilised – i.e. there was no need for different groups of experts for different parts of the framework. This is because although there are multiple AM subject areas covered within the scope of the framework (see section 5), they are all strongly interlinked and in the author's experience they are usually covered by the same job role in industry. And because the selection criteria for participants specifically targeted this job role (as described in section 7.2.1), each participant had the same type of expertise – hence it was a homogeneous group.

When a group is homogeneous, between 10-15 participants is usually sufficient for a Delphi study (Okoli and Pawlowski, 2004; Hsu and Sandford, 2007; Skulmoski et al., 2007) – therefore that was the aim in the case of this research. Aichholzer (2009) advises that a drop-out rate of up to 50% can be expected between rounds; therefore after this was factored in, the aim was to approach around 20 participants in total.

Another important factor regarding the number of participants is how many can actually be found in the time available that are both suitable and willing to participate. It was recognised that this was more likely to be the limiting factor in reality – according to Bernard (2012), sometimes a researcher will have to "take what they can get". If recruitment was especially difficult and fewer than the desired minimum of 10 participants were found, this would be resolved by relaxing the selection criteria in order to widen the potential recruitment pool (e.g. to include participants who may have had a more junior job role related to MD, such as a maintenance planner). It was recognised that these participants would have been less experienced, but this was considered more desirable than no experience. Ultimately, recruitment was relatively successful and sufficient participants were recruited anyway, so this was not necessary (see section 7.4.1).

7.2.3. Method for Participant Recruitment

For this study, participants were recruited via a targeted nominations method (Tracy, 2013; Magnusson and Marecek, 2015). This method is similar to the chain referral approach (also known as snowball sampling), which involves seeking recommendations for further participants from the existing ones (Okoli and Pawlowski, 2004; Skulmoski et al., 2007; Aichholzer, 2009; Ononiwu, 2013; Seidman, 2013; Tracy, 2013; Marchau and Van de Linde, 2016). One limitation of this method is the potential risk of bias – i.e. additional participants who are referred from the existing ones are more likely to have similar backgrounds and viewpoints. To counter this, the targeted nomination approach utilises specific individuals in target contexts, who start their own referral chains; i.e. there are multiple, separate referral chains that branch out into targeted groups (Tracy, 2013; Magnusson and Marecek, 2015). This can help to improve the diversity of the participants in comparison to the standard chain referral method (Tracy, 2013). The personal and professional networks of the author, the author's academic supervisor, and the author's industrial sponsor were utilised to reach out to relevant contacts in a several different contexts in order to source suitable participants. Participants were also recruited from 2 different countries with different MD cultures (i.e. the UK and Australia) in order to increase the range of the collected data.

Experts were engaged via a covering letter requesting their participation, as recommended by Aichholzer (2009) – see Appendix E for an example. This was followed by a short briefing at the start of their face-to-face interview to explain the background and purpose of this research.

7.2.4. Research Ethics

It is university policy for all studies involving human participants to seek ethical approval from the Biomedical and Scientific Research Ethics Committee (BSREC) prior to commencement. The application process consisted of mandatory training on research integrity and the completion of an ethical risk assessment to ensure that research participants were not subjected to harm. Fully informed consent was obtained from each participant via the completion of a Consent Form (see Appendix F), and a Participant Information Leaflet was also provided to ensure that each participant understood exactly what they are consenting to, and that they had the right to withdraw from the study at any time (see Appendix G). Other issues such as data security and participant confidentiality were also clearly explained to each participant (note that anonymity is a core principle of all Delphi studies anyway, as discussed earlier in section 7.1.1).

The application was successful and ethical approval was granted by BSREC (reference number: REGO-2016-1901).

It was agreed that the names of individuals and their respective companies would be redacted from any publications related to this research, and as a result they cannot be cited directly in this report.

7.3. *Pilot study*

The methodology described earlier in section 7.1 was tested via a pilot study before any real data was collected. The purpose of this pilot was to test for reliability (i.e. did the participants give consistent responses), validity (i.e. did the questions actually address the objectives of the study) and of course for any typographical or grammatical errors in the questions (Okoli and Pawlowski, 2004; Brace, 2013; Saris and Gallhofer, 2014). Those who took part in the pilot study trialled the entire Delphi methodology (including both the round 1 interview and the subsequent questionnaire format); they were asked to provide feedback afterwards in order to refine and improve the research design by answering the following questions – adapted from Brace (2013) and Saris and Gallhofer (2014):

On Reliability:

- Are the questions understandable? (i.e. complexity of wording, jargon, ambiguity)
- Do the instructions make sense? (self-completion questionnaire only)
- Is it feasible to retain interest / attention throughout the process? (i.e. are the question sets too long / boring?)
- Do the questions flow with a logical sequence? (i.e. not switch topic suddenly without reason)

On validity:

- Are all of the questions answerable? (i.e. were there any missing responses? Why? This is the most important measure of survey quality according to Saris and Gallhofer (2014)).
- Are the responses sufficient to perform the analysis?
- Was the intent of the questions reflected in the responses?
- Do the responses make it possible to address the objectives of the study?

On errors:

- Are there any errors in wording, e.g. typographical or grammatical?

For the pilot study, several suitable colleagues of the author from within the sponsor company – who matched the selection criteria defined in section 7.2.1 – were enlisted to take part (3 persons in total). This type of small scale, informal pilot study is an acceptable method for answering all of the questions listed above, as long as the participants match the selection criteria (Brace, 2013; Seidman, 2013). It is generally not recommended to use close colleagues or acquaintances as participants in the main study – because they may not feel free to talk openly for fear of compromising existing relationships, which may result in biased responses (Saldana, 2011; Seidman, 2013; Magnusson and Marecek, 2015). However, for a pilot study this type of participant is acceptable because the data collected is not actually used for analysis, whilst the trial is still able to provide suitable insight into the effectiveness of the data collection process. In fact, close colleagues are ideal candidates for a pilot study because they are easy to access and yet do not consume any valuable participants that could be used for the real study (which as discussed in section 7.2.2 may be difficult to recruit in sufficient numbers).

7.3.1. Pilot Study Feedback

Error! Reference source not found. below shows the comments received from the pilot study p articipants, and the actions taken to address them. Note that any actions that involved changes to the methodology have already been encompassed above – i.e. the methodology described earlier in this document is the final version.

Comments	Actions taken
“Don’t send the framework to interview participants in advance – it is too complex and detailed and nobody will read it. It will put them off more than it will help.”	Participants were only be sent a brief description of the framework sub-sections prior to their interview so that they knew the topics to be discussed – but not the entire framework.
“Instead, present the framework in person, one section at a time, with a discussion at the end of each section.”	Interviews were structured section-by-section to reduce complexity and to allow time for discussion before moving on to the next topic.
“Make it clearer what the optional practices are – present each option separately and ask them to choose the best option for their context, and explain why.”	Optional practices were given more emphasis during the interviews as advised. Framework v2 was also be adjusted so that optional practices were more visually pronounced.
“To successfully recruit participants, you really need to offer something in return – i.e. what’s in it for me? E.g. an opportunity to: • Learn something new • Confirm you are doing the right thing • Receive a free benchmarking / health assessment	These suggestions were incorporated into the participant recruitment covering letter.
“The first 2 questions are the most complex in the entire questionnaire – they are potentially off-putting. They should be moved to the end of section 1, and simplified as much as possible.”	Section 1 question order was adjusted accordingly and the offending questions were simplified as much as possible.
“The question numbering system is a little confusing because section 2 has no questions.”	Question numbering was reworked so that it no longer referenced the questionnaire sub-section in the question number.

"The free text / comments questions would be better with just 1 at the end of each section, rather than 1 at the end of every question. I didn't always have something to say for every question – make it optional or you will only encourage participants to abort the questionnaire."	The open comments sections were limited to one per framework section as suggested, and they were made optional. This may have caused some participants to skip this aspect of the questionnaire, but it likely helped to achieve a high response rate.

Table 6 – Summary of pilot study feedback – comments received and actions taken

7.4. *Results and Analysis*

7.4.1. Participant List

A summary of study participants is shown in **Error! Reference source not found.** below (note t hat some details have been redacted in this report in line with confidentiality agreements, as described in section 7.2.4). Each held a management / senior planning role within the MD area, and were recruited from a variety of maintenance-intensive contexts, as per the selection criteria outlined in section 7.2.1. A total of 12 participants took part, in line with the planned quantity that was defined in section 7.2.2 (i.e. a range of 10 – 15 participants).

Note that each participant's reference number, shown in the first column of Table 6 below (i.e. # 1 – 12), is used for reference throughout the analysis in section 7.4.2.

#	Name	Role	Company	Sector	Location	Interview Date
1	Anonymous Expert 1	Maintenance Manager	Redacted	Oil and Gas (Refining)	Redacted	27/01/17
2	Anonymous Expert 2	Planning Coordinator	Redacted	Power Generation (Nuclear)	Redacted	13/02/17
3	Anonymous Expert 3	Engineering Manager	Redacted	Chemicals	Redacted	15/02/17
4	Anonymous Expert 4	Engineering Manager	Redacted	Nuclear Reprocessing	Redacted	20/02/17
5	Anonymous Expert 5	Planning Control Manager	Redacted	Chemicals	Redacted	21/02/17
6	Anonymous Expert 6	Senior Planner	Redacted	Oil and Gas (LNG)	Redacted	07/03/17
7	Anonymous Expert 7	Senior Planner/Scheduler	Redacted	Oil and Gas (Offshore)	Redacted	15/03/17
8	Anonymous Expert 8	Principal Engineer Asset & Maintenance Systems	Redacted	Power Generation (Coal)	Redacted	06/04/17
9	Anonymous Expert 9	Maintenance Manager	Redacted	Power Generation (Coal)	Redacted	06/04/17
10	Anonymous Expert 10	Infrastructure Maintenance Manager	Redacted	Airports	Redacted	10/04/17
11	Anonymous Expert 11	Maintenance Manager	Redacted	Electricity Distribution	Redacted	12/04/17
12	Anonymous Expert 12	Maintenance and Asset Manager	Redacted	Steel	Redacted	13/04/17

Table 7 – Summary of study participants

7.4.2. Analysis of Data

A series of tables were used to record the analysis of participant's responses: i.e. the coding of round 1 responses, the construction of the questionnaire for round 2, and the analysis of the round 2 responses. The conclusions that were drawn from this analysis (i.e. the changes that were made to create Framework v2) were also recorded in the same tables. Table 8, shown at the end of this section, demonstrates this process with a selection of examples.

Each participant listed above in section 7.4.1 was interviewed according to the methodology outlined in section 7.1.2 of this report. The outcome of these interviews was a series of hand-written notes and annotations, documenting each participant's responses and comments. Each set of annotated notes was coded to concisely summarise the meaning behind each comment, and to allow equivalent opinions to be more easily identified. An example of this process can be found in the first 4 columns of Table 8 at the end of this section:

- The first column references the associated step from Framework v1;
- The second column contains the code name;
- The third column contains a detailed code definition;
- The fourth column references the participant(s) that the code was sourced from.

Any comments related to "red practices", i.e. the potential innovations in the framework that were discussed earlier in section 6.3.2, were recorded and analysed separately – Table 9, shown at the end of this section, demonstrates this process with a selection of examples:

- The first column references the associated step from Framework v1 and briefly describes the red practice.
- For the red practices that the author previously highlighted as potential innovations (see section 6.3.2), reasons are provided in the second column.
- The third column shows the participants who did not consider the practice to be novel (i.e. they had encountered it before). These practices were treated as new knowledge for the literature (i.e. category A as defined in section 6.3.2), rather than as innovations (i.e. category B); the participant's responses were subsequently used as a reference in Framework v2 (see Appendix D).
- For any red practices where all participants agreed that the practice was novel, comments are shown in column 4 from those participants who thought the practice was also significant and beneficial in their context (these practices therefore met the

criteria for category B – i.e. innovations – as defined in section 6.3.2). These comments were used as justification for any associated innovation claims, which will be discussed in more detail in section 7.5.1.

- The fifth column states the final result for each red practice – i.e. category A or B (i.e. new knowledge or innovation respectively).

After coding the responses from all 12 interviews, there were a total of 176 codes – far in excess of the desired range of 24-36 that was defined in the methodology for inclusion in the round 2 questionnaire (Graham, 2008). Therefore, the prioritisation mechanism that was described earlier in section 7.1.3 was applied; this process is demonstrated in column 5 of the example table shown later in this section (i.e. Table 8). If a suggestion was accepted, it was labelled as such with the prioritisation mechanism clearly shown in brackets to provide justification (i.e. A, B or C). If a suggestion was selected for involvement in round 2, then it was labelled "Round 2". Through this prioritisation process, the number of questions for round 2 was reduced from the initial 176 to 29 – which was within the desired range of 24-36 as set by the methodology in section 7.1.3.

The round 2 questionnaire was constructed according to the methodology outlined in section 7.1.3 of this report. The online survey software Qualtrics[2] was utilised, as provided by the university. The questionnaire was sent out to all 12 interview participants, and 10 out of the 12 returned a completed questionnaire. Every effort was made by the author to encourage participants to complete their questionnaires (i.e. sending multiple reminders, providing notice in person during the interview, attempting to get participants invested in the research goals), yet a 100% response rate was ultimately not achieved. However, Aichholzer (2009) advises that a drop-out rate of up to 50% can be expected for Delphi questionnaires, so the achieved response rate was considered to be reasonably successful. 10 participants was just within the desired range of 10-15 participants as defined in the methodology (see section 7.2.2), so this was considered enough to continue with the analysis without compromising the research outcomes. The 2 non-responses were likely due to a combination of the participants being busy professionals with their own priorities, and a small number of unfortunate technical errors with the survey software, which may also have been a contributing factor (i.e. several participants reported that they could not access the questionnaire because they did not receive their initial email invitations – these had to be

[2] For further information see: https://www.qualtrics.com/uk/research-core/

resent, which may have caused enough inconvenience for the participants to ultimately reject the invitation). If the questionnaire was shorter then it is possible that it may have achieved a 100% response rate, but as discussed above, a significant effort was already made to reduce the number of questions down from the initial 176 to 29 – and this was probably the minimum number of questions that could reasonably be achieved without compromising the integrity of the research.

For the 29 codes that were included in round 2, the questionnaire responses were recorded as demonstrated in column 6 of the example table shown later in this section (i.e. Table 8). They were presented in a simple distribution list format, to show the spread of opinion across the available response options, as discussed in section 7.1.3. Note that because no additional practices were suggested via the open comments section of the questionnaire during round 2, a third round was not necessary (in accordance with the methodology, as summarised in section 7.1.3) and therefore data collection was stopped at this point. The process for drawing conclusions on the mandatory / optional nature of each additional practice is demonstrated in column 7 of the example table shown later in this section (i.e. Table 8).

FW v1 Step	Code (Delete / Change / Move / Add / Guidance)	Definition	Source (Participant)	Priority Decision	Round 2 Result	Changes made to framework v2 (all step numbers refer to v1 steps)
1.01	(Add) Handover Documentation Pack	Add a new step after 1.01 to formalise documentation handover. Whenever a new asset is installed, the Project Team responsible must hand over all of the new asset's records and documentation to the maintenance team (e.g. installation / testing certificates, as-built drawings / diagrams, data sheets, operation and maintenance manuals etc.). This information will be required to set up the asset in the CMMS, and determine spares holdings and maintenance requirements.	3, 6, 8, 9	Round 2	Str Ag (6) Ag (4) Sw Ag (0) Sw Dis (0) Dis (0) Str Dis (0)	All participants agreed with this suggestion, with the majority strongly agreeing. Therefore a new step has been added to the framework to provide "documentation pack handover" from Project Team to the Maintenance Team.
1.02	(Guidance) Standardised Numbering System	It is beneficial for Asset Record ID numbers to be created according to a formal, standardised numbering system, which is coded so that each character carries a defined meaning (as opposed to a random number). This helps to establish a common understanding throughout the business, which is particularly useful in multi-site scenarios. International standards are available, such as the German "KKS" numbering system, developed for the power generation sector (Siemens, 2010).	7, 8, 9, 10	Accept (B)		The guidance shown will be added to the commentary for this step.
1.02	(Change) Linear Assets	Linear assets (e.g. roads, railways, runways) are not well represented in the current document, and step 1.02 needs to be modified slightly to accommodate them (as an additional option, where applicable depending on context). Linear assets can utilise a hierarchy format to some extent, but they require more than this. Consider that a linear asset such as a runway will be registered in the CMMS in say 100m sections, but rather than just a "parent-child" relationship (i.e. a hierarchy), the CMMS also needs to distinguish which assets are adjacent to each other, i.e. the sequence in which they are arranged. This is needed to plan inspections and pinpoint the location of defects. Most CMMS packages are not able to do this as standard (e.g. SAP, Maximo).	10	Accept (A)		Step 1.02 modified to give consideration to linear assets when designing asset register structure. CMMS implementation specification modified to include functionality to enable relationships to be defined between linear assets.
1.05	(Change) Criticality Visibility	This step should be expanded to include some additional supporting CMMS functionality. It is important that the Criticality rating of the asset is clearly visible within any WO Requests or WOs raised against that asset. This information is essential during work prioritisation, to highlight the importance of the work and the potential consequences if it is not carried out on time (e.g. a breach of legal compliance or potential plant breakdown).	6, 7, 8, 11, 12	Accept (C)		CMMS functionality added to this step.

Table 8 – A selection of examples to demonstrate the analysis of participant's responses (improvement suggestions and contextual guidance)

Framework Step containing "red practices"	"Red practices" that are potentially innovative, and why	Witnessed in industry by participant	Comments providing reasons why the practice is significant and beneficial in the participant's context)	Result
1.09 Modify Asset Record in the event of a change	The use of the CMMS to log formal requests for changes to Asset Data, and to provide a record of such changes, is potentially innovative. This is normally done via a paper form system, and would be more robust and time-efficient if recorded via a specific WO Request in the CMMS.	2, 6	-	A
5.16 Review Schedule progress against plan at the close of each working day	-	2, 4, 5, 7, 12	-	A
7.06 Create WO Request (Type = Improvement)	The use of the CMMS to log improvement suggestions and to manage improvement activities is potentially innovative. Improvement suggestions are normally logged in a separate system (if at all) – but since improvement activities often utilise maintenance resources, it would be better to fully integrate them into the CMMS, so that they can be screened, planned, scheduled and executed alongside normal maintenance tasks.		"Great idea to manage improvements via the CMMS to track, analyse and quantify. The actual improvement activity uses the same resources as maintenance activities (i.e. technicians), so this makes perfect sense" (Participants 7, 9). "Managing improvements via the CMMS would provide greater focus / visibility for the maintenance team, rather than in several external systems that nobody knows how to use" (Participant 8).	B

Table 9 – A selection of examples to demonstrate the analysis of participant's responses ("red practices")

7.5. *Conclusion*

A total of 176 improvements to Framework v1 were sourced from industry experts via a modified Delphi methodology. Framework v2, which will be discussed in more detail in section 8, was developed by incorporating these improvements, which consisted of additional industry-based practices and guidance.

7.5.1. Innovations

Recall from the beginning of section 7 that several "red practices" were added to Framework v1 directly by the author – without references to the literature – which could have been either: (A) new knowledge that was practiced in industry but was not recorded in the literature, or (B) innovations that were conceived by the author during the development of the framework, that improved upon the content found in the literature and went beyond the practices found in industry. After conducting an analysis of participant's responses, 21 of these red practices were found to fit category A, and 3 were found to fit category B. For the 21 category A practices, the participant's comments verifying that the practice genuinely takes place in industry were utilised as references in Framework v2, enabling this research to add to the body of knowledge. The 3 category B practices are shown below in Table 10 below, along with the relevant participant's comments that demonstrate that the practices are innovative.

"Red practices" that were considered novel by all participants	Participant's comments providing reasons why the practice was also significant and beneficial in their context
The use of a specific WO Status to show that MT scheduling is complete and ST scheduling is required, is potentially innovative. Normally there is no clear identifier in the CMMS between these key process stages, which if present would improve workflow efficiency.	"Can see a clear benefit as this status provides a "gate" between the MT and ST scheduling phases, making it easier to identify WOs that are ready for ST scheduling, enabling smoother workflow" (Participant 6).

"Red practices" that were considered novel by all participants	Participant's comments providing reasons why the practice was also significant and beneficial in their context
The use of the CMMS to capture the reasons for any execution delays via specific Delay Codes, is potentially innovative. Whilst execution delays (in hours) are commonly recorded in the CMMS, the reason for each delay is not. Doing so would enable this data to be trended to reveal the biggest cumulative causes of delay, to identify opportunities for improvement.	"Can see the benefit of trending this information to identify areas for improvement" (Participants 6, 7). "Practiced manually via a paper system currently, would be easier to report if done automatically via the CMMS" (Participant 9).
The use of the CMMS to log improvement suggestions and to manage improvement activities is potentially innovative. Improvement suggestions are normally logged in a separate system (if at all) – but since improvement activities often utilise maintenance resources, it would be better to fully integrate them into the CMMS, so that they can be screened, planned, scheduled and executed alongside normal maintenance tasks.	"Great idea to manage improvements via the CMMS to track, analyse and quantify. The actual improvement activity uses the same resources as maintenance activities (i.e. technicians), so this makes perfect sense" (Participants 7, 9). "Managing improvements via the CMMS would provide greater focus / visibility for the maintenance team, rather than in several external systems that nobody knows how to use" (Participant 8).

Table 10 – "Red practices" that were found to be innovative, based on participant's responses

For the 3 category B practices, generally speaking they were all related to additional CMMS functionality that can be achieved through creative use of configuration settings. All were certainly novel according to the 12 participants, but the appreciation of the benefits was more subjective – positive comments were only received in a limited number of contexts (i.e. typically contexts that had very mature CMMS processes – those with basic systems did not appreciate the benefit), therefore it is only reasonable to claim these as minor innovations that apply only in specific cases. In relation to the outcomes of this project they will be considered as minor additional innovations alongside the main innovation claim (which is of course the framework itself) – a summary of all project innovations can be found in section 10 of this report.

Several positive comments were also received from participants that strengthen the main innovation claim for this project, regarding the general concept of the framework and its prospective application in industry:

- “A formal business process for MD – agreed, documented, signed off, and aligned to the functionality of the CMMS – is very valuable; such a tool is not available in my organisation. This causes several problems: a lack of consistent strategy, and poor data quality which prevents analysis and improvement in performance.” (Participant 10).
- “In reality, most CMMS implementations are badly done. An implementation specification such as the one you are proposing would be a useful guide to prevent this.” (Participant 7).
- “Including a section on improvement is a good addition that is often left out of MD systems – this is a major component of ISO 55000 and needs to be integrated into the MD process if it is to work” (Participants 8, 12).
- “The MD process certainly needs to vary to suit the manufacturing process if it is going to be effective. Different industries will have different requirements, and your framework rightly allows for this.” (Participant 12).

7.5.2. Further Work

During the round 1 interviews, several interesting points were raised by participants during the open discussion that could potentially warrant further study:

- “It’s all very well to have an effective MD process – but how do you actually get people to follow it?” (Participant 1).
- “In a culture change scenario, which parts of the process do you implement first? Which are core, which are just a bonus? Is there a scale of maturity?” (Participant 3)
- “Simplicity and ease of use of the CMMS have a huge impact on this. You have to make people’s lives easier, not harder, to be successful.” (Participant 5).
- “CMMS implementations are often rushed. Organisations sometimes think that if they spend more money on an expensive and elaborate CMMS, they will get better results. But a complex system just confuses users, massively increases the implementation costs, and ultimately makes the problems worse.” (Participant 6).
- “CMMS implementations take around 3 years to do properly – they cannot be rushed. The goal is to create a user-friendly and efficient system, to reduce the admin burden. Every additional minute that it takes to close out a WO, multiplied by thousands of WOs per year, costs a lot of time and money. Make it easy for people

to enter the data and the quality also improves – user-friendliness is paramount." (Participant 11).

Many of these comments relate to the difficulties with respect to organisational change in a MD context – i.e. how to implement new practices in a business that already has existing ways of working and expectations. This certainly seems to be a genuine industry problem that could be researched further at a later date. Some of these issues were encountered during the implementation of the framework at the sponsor company, and they will be discussed further in section 9. Based on the participant's comments, a significant factor seems to be ease of use for the people involved in the change – particularly with regard to the CMMS – a point that was also raised previously in the literature review from section 5.3.1.

8. Presentation of Framework v2

Section 7 described the process by which expert opinion from industry was utilised to validate and improve upon the initial literature-based framework design (i.e. Framework v1), via a modified Delphi methodology. A total of 176 improvements were sourced via this approach, which involved experts from a variety of maintenance-intensive contexts including the chemical, utilities, infrastructure, oil and gas, power generation, nuclear, and steel industries. Framework v2, which was developed by incorporating these improvements, is presented in full in Appendix D. An excerpt will be shown in this section to demonstrate the framework concept and illustrate its associated innovation claims.

8.1. *Overview*

Framework v2 is broken down into 6 sub-sections that are summarised below. Notice that this is one fewer than the original 7 sections that were featured in Framework v1 (see section 6.2); the first two sections of the framework were merged together as a result of an improvement suggestion elicited from industry experts via the Delphi study.

1. **Asset Registration & Maintenance Requirements Analysis –** includes new asset installation / existing asset modification; assets are registered in the CMMS (Computerised Maintenance Management System) with all required data and are categorised appropriately; assets are decommissioned at end of service and CMMS data is archived; maintenance requirements are identified and routines are registered in the CMMS, with a defined scope of work, due date and frequency.
2. **Emergent Work Request & Screening –** asset breakdowns / defects are identified and corrective maintenance is formally requested; each request is reviewed, screened (i.e. approved / rejected), prioritised according to urgency, and then assigned to a planner for resolution; high priority / emergency tasks are processed differently to achieve faster resolution times.
3. **Planning** – a safe and effective execution method is determined for each task; tasks are broken down into discrete steps with defined durations and manning requirements; all required resources are determined (i.e. parts, tools, access); materials are sourced and staged ready for execution.

4. **Scheduling** – execution dates are optimised according to resource availability, task urgency, and production requirements; work assignments are allocated for individual maintenance technicians.
5. **Execution** – tasks are safely executed, reviewed and recorded as complete in the CMMS; data is captured for failure analysis and performance measurement.
6. **Improvement** – performance data is collected and analysed to identify opportunities for improvement; significant or recurring failures are analysed to determine the root cause; improvements from both sources are collated, assessed for cost / benefit, actioned to deliver improvement, and reviewed to quantify the benefits realised.

Fig. 9 below shows the relationships between these 6 sections at a high level. In the full framework document (i.e. Appendix D), each section has its own flowchart containing a number of detailed process steps, and these flowcharts are accompanied by a series of tables presenting clear definitions, justifications and references for each step. However, the entire framework cannot be reproduced here due to its size; therefore one section has been selected as an example to demonstrate the core concept – i.e. section 2, Emergent Work Request and Screening.

A Tailorable Framework of Practices for Maintenance Delivery – Overview

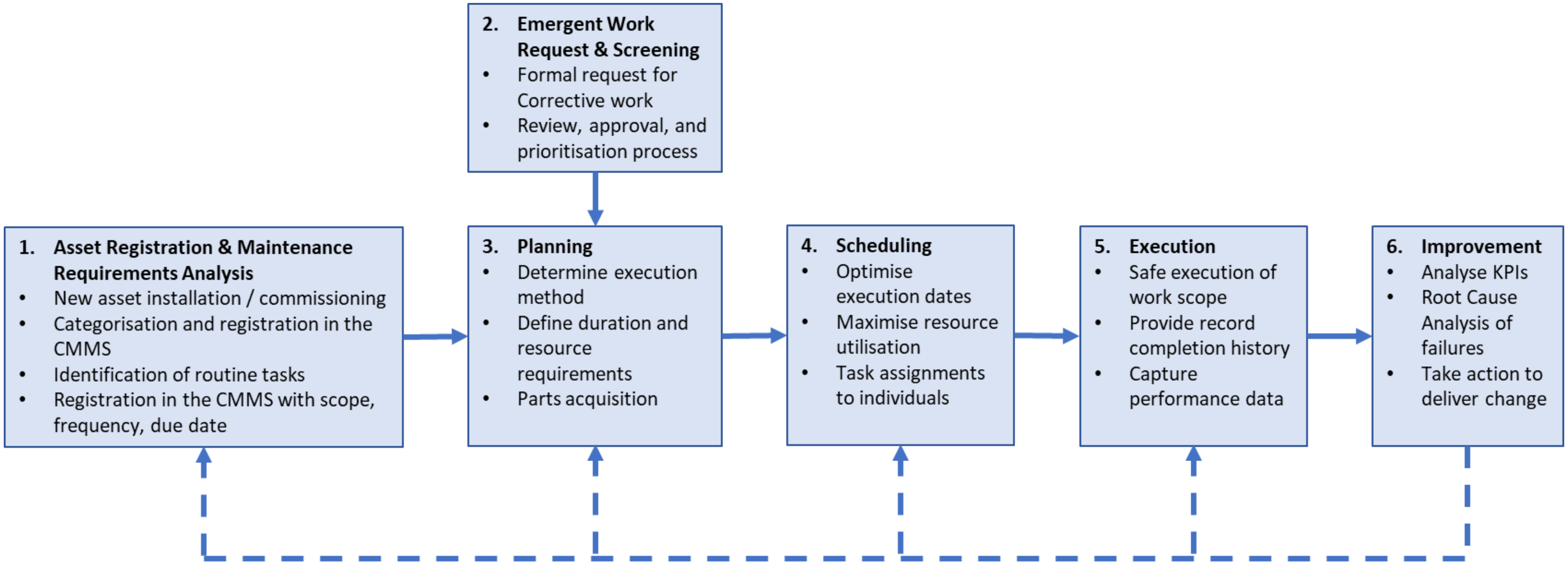


Fig. 9 – An overview of the main sub-sections of Framework v2

8.2. *Example Framework Section – Emergent Work Request & Screening*

The basic principles of an emergent work request and screening process are as follows (Suttell, 2005; Institute of Nuclear Power Operations, 2010; Peters, 2014; Duffuaa and Raouf, 2015):

- When a defect or failure is identified, a Work Order Request (WOR) is raised in the CMMS in order to request a solution from the maintenance team. Failures can be classified as follows:
    - Either a complete loss of function (Breakdown) or a partial loss of function (Defect) (Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017).
    - This loss of function can be either intentional ("Run to Failure") or unintentional (Hickman, 2011; Ismail, 2014; Peters, 2014; Duffuaa and Raouf, 2015).
    - The failure can either be discovered via a planned inspection ("Inspection Based") or by chance (Anonymous Expert 7, 2017; Anonymous Expert 11, 2017).
- WORs are screened regularly – i.e. they assessed to determine the scope of the problem, and a decision is made to either approve or reject each request (this is sometimes referred to as "gatekeeping"). Approved work is clearly prioritised so that the most urgent tasks are addressed first.
- Approved WORs become Work Orders (WO), allowing them to move forward to the next stages of the MD process for planning, scheduling and execution. They are assigned to a dedicated planner to ensure that each task has clearly defined ownership.

Whilst these basic principles are common to any emergent work screening process, there are numerous options to consider when designing a more detailed business process. The main premise of the framework is that the most appropriate selection depends on the context, as the examples from framework section 2 below will demonstrate.

Fig. 10 below shows the complete flowchart for framework section 2. Note that each step is labelled with a number and these labels are utilised for reference in the accompanying commentary table, which begins on the following page (i.e. Table 11). Steps shaded in green require CMMS support, whereas steps shaded in blue are non-CMMS activities (e.g. meetings). Any optional practices are clearly highlighted via purple text, and guidance for selecting the appropriate options based on the context is also provided in the accompanying tables. Interactions between each step are shown via directional arrows, and the person responsible for executing each step is shown via a pink annotation (where relevant).

In line with one of the objectives of the framework, as set out earlier in the problem definition (see section 5.3.1), a detailed CMMS implementation specification has also been developed for each framework step (where appropriate – this feature was not applicable for some non-CMMS activities). The final column in the accompanying tables provides this specification, which is fully tailorable in line with the optional practices that are selected. This is to enable the end user to implement and configure their CMMS in full alignment with their tailored business process. The format for the configuration specification is presented as follows:

> [CMMS Component, Subset of Component] Name of Subset (= Property of Subset*) (*where applicable; not all subsets require specific properties)

For example:

> [WO, Field] WO Type = Routine
>
> [Asset Record, Field] Asset Criticality = Critical
>
> [WO Request, Status] Complete
>
> [Asset Record, Function] Ability to flag fields as mandatory

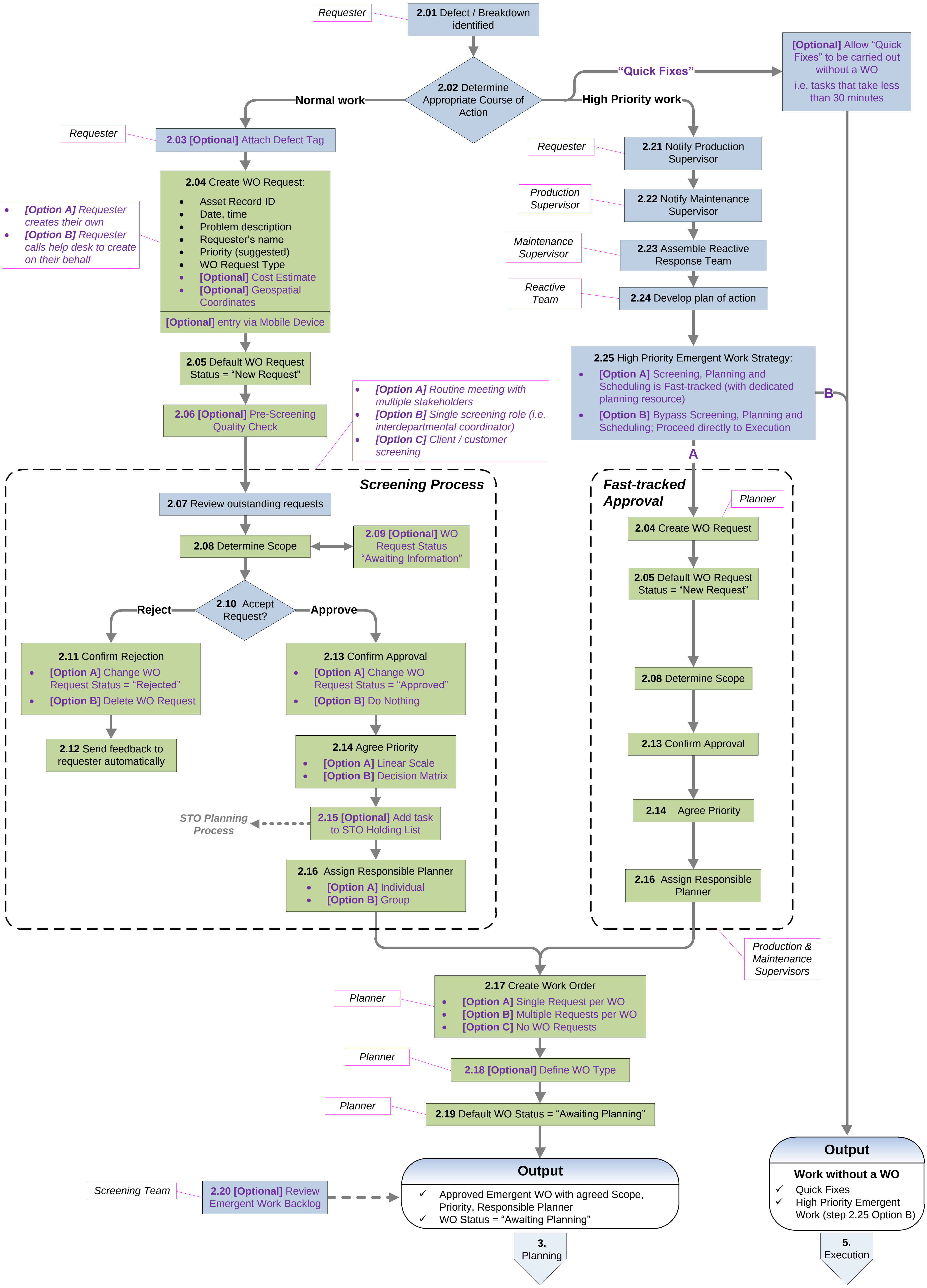


Fig. 10 – Framework Section 2 flowchart – Emergent Work Request & Screening

Process Step	Definition	Justification	CMMS Implementation Spec.
2.01 Defect / Breakdown identified	An asset has failed in service; there is either a complete loss of function (Breakdown) or a partial loss of function (Defect).	The MD process must be capable of managing corrective actions in response to failure, as discussed in section 5.3.3 of this innovation report. This step provides an input into the process for such events.	N/A
2.02 Determine Appropriate Course of Action	The person who discovered the failure makes an initial assessment of the situation to determine the next course of action.	The appropriate response depends on the nature of the failure, which will fall into one of the following categories: • **Normal Work** – the vast majority of failures should fall into this category, e.g. generic defects and non-critical breakdowns. The full screening process should be followed as indicated on the flowchart. • **High Priority Emergent Work** – these failures need to be addressed more urgently and therefore follow a different process (e.g. a critical asset failure resulting in a production stop or a safety / environmental / legal risk). • **Quick Fixes [Optional]** – In some contexts, tasks that take less than 30 minutes to execute may be permitted to completely bypass the normal screening process and proceed directly to execution. No Work Order (WO) is required; technicians can go ahead and resolve them autonomously (Hickman, 2011; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 8, 2017). See below for detailed arguments for and against this.	N/A
	Arguments for and against allowing "Quick Fixes" to be carried out without a WO, essentially allowing the screening, planning and scheduling processes to be bypassed for quick and simple tasks.	**Against:** The process for screening Emergent Work requests is a vital part of work control, ensuring that only valid requests are approved for execution (and consequently for the consumption of limited resources, which must be allocated wisely) – the key principle is that no work can go ahead without a WO, and a WO can only be created via an approved WO Request that has been through the formal screening process (involving review by all necessary stakeholders) (Anonymous Expert 5, 2017; Anonymous Expert 11, 2017). These rules ensure the validity of all work entering the system, and ensure that resources are allocated according to agreed priorities. If "Quick Fixes" are allowed to bypass these rules, then it undermines the entire process because resources are not carrying out the work that was agreed; this ultimately results in poor maintenance performance (Shafeek, 2014). **For:** However, there are some experts who say that tasks that require less than 30 minutes to execute should be an exception. In infrastructure / utilities contexts where work is executed at very remote locations, if a defect is found (often during a routine inspection) it is more practicable to address it there and then, to avoid a return visit – a WO can always be recorded in the system retroactively, ensuring that work history is still recorded (Hickman, 2011; Anonymous Expert 11, 2017). **Against:** However, some say that if users are able to record work retrospectively, there is a risk that they simply forget to do so, and then the failure cannot be recorded or analysed, making it more likely to recur (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017).	

Process Step	Definition	Justification	CMMS Implementation Spec.
2.03 [Optional] Attach Defect Tag	A hand-written tag is physically attached to the failed asset (Peters, 2014). The use of such tags is only recommended in certain contexts; arguments for and against are provided in the next column.	Comments in favour of using Defect Tags: • Tags provide a visual indication that the problem has already been reported, to prevent duplicate WO Requests (Anonymous Expert 2, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017); • Dated tags make it easier to see how long the problem has existed, to encourage a timely resolution (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017); • Tags are essential for safety reasons during maintenance execution. They provide a clear, visual indication of which asset the technician should be working on, to prevent accidental exposure to live equipment (Anonymous Expert 5, 2017; Anonymous Expert 6, 2017); • Tags are useful as a visual warning of a potential hazard (e.g. a chemical leak) (Anonymous Expert 9, 2017). Comments against the use of Defect Tags: • Paper tags can suffer from perishability, particularly in outdoor environments (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017); • Tags can get left behind after the task is completed, leading to misinformation (Anonymous Expert 5, 2017); • Tags can be onerous to fill out, which discourages people from reporting defects (Anonymous Expert 7, 2017); • If a second defect occurs on the same asset, it may never get reported because there is already a tag present (Anonymous Expert 7, 2017); • Some CMMS packages can automatically inform the user if there is a duplicate WO Request (Anonymous Expert 8, 2017; Anonymous Expert 11, 2017); • In contexts where the asset is used by the general public / customers, “defect” tags would have a negative effect on customer perception and public relations (Anonymous Expert 10, 2017; Anonymous Expert 11, 2017); • Tags are not practicable in utilities / infrastructure contexts, where assets are spread over a huge geographical area (Anonymous Expert 11, 2017).	N/A

<table>
<tr><th>Process Step</th><th>Definition</th><th>Justification</th><th>CMMS Implementation Spec.</th></tr>
<tr>
<td>2.04

Create WO Request</td>
<td>Create a formal request for Emergent Work via the CMMS (Howard, 2004; Hickman, 2011; Ramskill, 2014; British Standards Institute, 2015f). The following mandatory fields are required (Monsanto, 2007; Peters, 2014; Ramskill, 2014; Shafeek, 2014; Duffuaa and Raouf, 2015):
- Asset Record ID
- Date, time
- Problem description
- Requester's name
- Priority (suggestive only at this stage)
- Asset Criticality
- WO Request Type (the following types are recommended so that requests of a different nature can be managed via separate processes):
o Corrective action request (i.e. in the event of a defect or breakdown) (Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017)
o Modification / Change Request (i.e. step 1.01) (Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017)
o WO Due Date Deferral Request (i.e. step 4.07) (Anonymous Expert 6, 2017).
- [Optional] Cost Estimate. In contexts where maintenance execution is entirely outsourced, a cost estimate or quotation is required because cost is often the most significant factor in the approval decision (Anonymous Expert 10, 2017).
- [Optional] Geospatial mapping data. Coordinates are entered to pinpoint the defect location; this functionality may only be applicable in contexts with large civil structures (e.g. a runway) or where assets are spread over a large geographical area (Anonymous Expert 10, 2017).

Other information may be entered into the WO Request at this stage (depending on the knowledge of the requester); though these fields should not be mandatory:
- Photo / attachment (Anonymous Expert 1, 2017)
- Suggest materials requirements (Anonymous Expert 7, 2017)
- Suggest access requirements (Anonymous Expert 7, 2017)
- Suggest Work Team / Trade Skill requirements (Anonymous Expert 8, 2017)
- Failure Codes (Fault / Damage / Cause / Remedy) (Anonymous Expert 8, 2017; Anonymous Expert 11, 2017)</td>
<td>Note that the Priority classification is only suggestive at this stage – the final decision is made by the screening group in step 2.14 (Institute of Nuclear Power Operations, 2010).

It is important that the Criticality rating of the asset is clearly visible within any WO Requests or WOs raised against that asset. This information is essential during work prioritisation, to highlight the importance of the work and the potential consequences if it is not carried out on time (e.g. a breach of legal compliance or potential plant breakdown) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).

Regarding who should create WO Requests, 2 options are presented – the correct choice depends on the context. Some sources suggest that requests should be handled via phone by an administrator / dispatcher, who then creates WO Requests on the requester's behalf (Kherun et al., 2002; British Standards Institute, 2004; Suttel, 2005; Peters, 2014). This reduces user training requirements and simplifies access control arrangements (Anonymous Expert 3, 2017; Anonymous Expert 4, 2017). A similar method involves filling out paper defect slips manually, which are then collected and entered into the CMMS by an administrator (Anonymous Expert 4, 2017). However, according to Kherun et al. (2002), this method can result in poor quality information if the call handler is not technically skilled (as is often the case). An alternative according to Peters (2014) and Duffuaa and Raouf (2015), is that everyone in the organisation should have the authority to raise their own WO Request – there is less room for misunderstanding if the request is made first-hand. This generally improves the quality of the information – i.e. the person who saw the failure first hand can often describe it best (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). However, this approach is not appropriate in contexts where requests are made by non-technical persons (e.g. members of the public, passengers, tenants etc.) (Anonymous Expert 10, 2017).</td>
<td>[WO Request, Field] Asset Record ID, Date, Time, Problem Description, Requester's Name, Priority, Asset Criticality, Photo / attachment, Materials Requirements, Access Requirements, Work Team, Failure Codes (Fault / Damage / Cause / Remedy)

[WO Request, Field] WO Request Type = Breakdown, Defect, Change Request, or Due Date Deferral Request

[WO Request, Function] Automatically record Date, Time, Requester's Name

[WO Request, Field] Asset Criticality = (copied from Asset Record)

[WO Request, Field] Geospatial coordinates

[WO Request, Function] Geospatial mapping

[WO Request, Function] Ability to restrict access for creating WO Requests to authorised persons</td>
</tr>
</table>

Process Step	Definition	Justification	CMMS Implementation Spec.
	[Optional] The WO Request is created via a mobile device that interfaces with the CMMS, rather than from a fixed computer terminal. This does not alter the content of this step, only the end-user experience. Additional CMMS functionality will be required to enable this optional feature.	This step is a good candidate for data entry via a mobile device in the field, which enables the technician to enter data without returning to the office. This reduces admin time and improves "Wrench time" efficiency (i.e. % of time spent per day actually doing maintenance). Some CMMS packages are available with mobile functionality (at an extra cost) (Anonymous Expert 11, 2017). Mobile devices are particularly useful in contexts in which assets are spread over a large geographical area, so that technicians can access the CMMS remotely to enter and retrieve data in a timely manner (Anonymous Expert 11, 2017).	[CMMS, Function] WO Request via mobile device, with suitable user interface
	A note on the relationship between WO Requests and WOs (not shown on flowchart because this is a one-off implementation consideration):	**[Optional] –** In some contexts it is preferable to completely omit WO Requests from the MD Process. The alternative is to directly create a WO at step 2.04, with a "New Request" Status, and simply review this during the screening meeting. The advantage of this approach is that it is simpler to manage (i.e. there is only 1 CMMS "entity" instead of 2 for every task) – and simplicity increases the likelihood that the process will be followed willingly (Hickman, 2011; Anonymous Expert 12, 2017). However, this approach is only suitable in contexts where the CMMS package is able to provide a WO with all of the same fields and functionality that are available in a WO Request. In the author's experience, it usually does not – for example the following WO Request functionality is not available within a WO in SAP, a widely used CMMS package (Liebstuckel, 2012): • the ability to define request types (see step 2.04) • the ability to record failure codes (see step 5.40) • the ability to record detailed failure history and technician comments (see step 5.35) • the ability to assign multiple requests to a single WO (see step 2.17, Option B) Depending on the CMMS package in use, the functionality listed (and perhaps others) may or may not be available if WO Requests are omitted from the MD process. This framework will continue to be written with a WO Request entity present: if the option is selected to omit it, simply treat any mention of "WO Request" as a preliminary WO with the status = "New Request" (the MD process will remain the same in either case, i.e. all requests must be screened and approved before any work is authorised). However, please ensure that any desired WO Request functionality encountered in this framework is available within the WO of the CMMS package before continuing with this option.	
2.05 Default WO Request Status = "New Request"	New WO Requests have the default status "New Request".	So that new work can be easily identified during the screening process (Monsanto, 2007; Hickman, 2011; Ismail, 2014; Duffuaa and Raouf, 2015).	[WO Request, Status] New Request (default) [CMMS, Function] Search for and list out WO Requests by Status

Process Step	Definition	Justification	CMMS Implementation Spec.
2.06 [Optional] Pre-Screening Quality Check	If the Screening Process consists of a routine meeting with multiple stakeholders (i.e. Option A below), it may be appropriate to carry out a preliminary quality check on all new WO Requests prior to the screening meeting. This step is unnecessary if Options B or C are selected.	The following checks should be carried out for all new WO Requests prior to the screening meeting: • The Maintenance Team Leader / Supervisor should review all new WO Requests before the screening meeting to determine the full scope of work, investigate any information gaps, and delete any duplicates. The aim is to ensure that all required information is available during the screening meeting, so that a prompt decision can be made (Anonymous Expert 4, 2017; Anonymous Expert 9, 2017). • The Shift / Production Manager should sift through all new WO Requests and give a nominated priority prior to the screening meeting (to be discussed further and agreed at the meeting). The aim is to streamline the list to make the screening meeting more time-efficient (Anonymous Expert 2, 2017).	[WO Request, Status] New Request (default) [CMMS, Function] Search for and list out WO Requests by Status [WO Request, Field] Priority
2.07 Review outstanding requests	New WO Requests are screened to determine if they should be accepted, and then sent forward for planning and execution. With regards to the methodology used for the Screening Process, the following options are available: • **[Option A]** In a manufacturing environment, different departments (e.g. production, maintenance, safety) may have very different opinions as to which work should go ahead, and which is the highest priority; therefore most sources advocate a formal routine meeting (i.e. at least daily / shiftly) to allow all stakeholders to engage in the decision (Al-Turki et al., 2014; Peters, 2014; Duffuaa and Raouf, 2015). • **[Option B]** Alternatively, a single person can carry out the screening role provided that they are able to fairly balance the needs of all departments – i.e. if a dedicated production / maintenance coordinator role is in place (Monsanto, 2007; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017). • **[Option C]** Another option, which may be more suitable in a Facilities Management (FM) environment, is for a client / customer to screen all requests and make the decision directly (Kherun et al., 2002; Peters, 2014).	Multiple sources agree that WO Requests should pass through a screening process to ensure that only valid and meaningful work enters the MD process (Suttell, 2005; Institute of Nuclear Power Operations, 2010; US Department of the Army, 2013; Peters, 2014; Ramskill, 2014; Duffuaa and Raouf, 2015). Regarding option A, the following attendees are recommended for a Screening Meeting: - It is essential for Production and Maintenance Supervisors to be present, as they have a good working knowledge of the asset and its priorities (Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017). - Also include those who are ultimately responsible for asset performance (i.e. Production Manager / Maintenance Manager / Asset Manager), as they are key stakeholder(s) in any prioritisation decisions (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). - Health, safety and environmental representatives, and STO representatives can assist if applicable (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017). - It is useful to give technicians the opportunity to attend on occasion, in order to build awareness of the planning process (Anonymous Expert 7, 2017; Anonymous Expert 12, 2017). Screening meetings are best held little and often, to prevent the formation of an unmanageable stockpile of new requests. A quick, focused meeting every morning (approx. 10 – 15 minutes) should be sufficient to screen all new requests from the last 24 hours (Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). For larger sites, separate screening meetings can be held for each plant area, in order to reduce the request volume down to manageable levels (Anonymous Expert 8, 2017) In contexts were shift work is necessary, a screening frequency of “daily” may not be suitable – at the start of every shift may be more appropriate (Anonymous Expert 4, 2017).	[CMMS, Function] Search for and list out WO Requests by Status

Process Step	Definition	Justification	CMMS Implementation Spec.
2.08 Determine Scope	The full scope of the potential Emergent Work is determined so that a decision can be made as to whether or not it should be progressed (British Standards Institute, 2015f). If the scope is not clear, the screening team need to rectify this so that when the task moves forward to planning, there is a clear objective for the task. This information should be clearly recorded in the WO Description, and it should also be made certain that the correct Asset Record is selected in the WO, so that the work is recorded against the correct asset to enable performance monitoring and improvement (Baker, Booth and Wilson, 2013; Ismail, 2014; Shafeek, 2014).	This scope should be clear based on the information entered into the Problem Description field by the requester. The Pre-Screening Quality check in step 2.06 also ensures a clear scope description prior to screening. At this stage, it is also helpful if the screening team add any additional planning information that they can to the WO Request, to assist the planner during the next stage of the process: e.g. resource requirements, suitable execution methods, duration estimates. The attendees of the screening meeting are usually knowledgeable enough to offer some useful insight (but take care that this does not unnecessarily prolong the meeting) (Anonymous Expert 7, 2017).	[WO Request, Field] Problem Description
2.09 [Optional] WO Request Status = "Awaiting Information"	If it is not possible to determine the full scope of work during screening without further investigation, the WO Request should be added to a holding list using the status "Awaiting Information". Responsibility should be assigned to someone during the screening meeting to investigate and return with clarification.	It may not be possible to obtain a thorough scope of work from the requester – for example in an FM environment were the requester is not technically skilled (Kherun et al., 2002). Even in a manufacturing environment were requests are created by skilled technicians, the problem description can occasionally be unclear and require further investigation.	[WO Request, Status] Awaiting Information
2.10 Accept Request?	A decision to accept or reject the request is made based on the defined scope of work (Howard, 2004; Monsanto, 2007; Hickman, 2011; Ramskill, 2014).	Possible reasons for rejection include duplicate or vague requests (Monsanto, 2007; Peters, 2014; Ramskill, 2014), or if the cost of the work would outweigh the benefits (Kherun et al., 2002; Howard, 2004).	N/A
2.11 Confirm Rejection	If the request is rejected, then action must be taken in the CMMS to demonstrate this and remove it from the list of outstanding requests (Hickman, 2011; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017).	- **[Option A]** Use a specific Status to flag the rejected work – e.g. "Rejected". This method removes the request from the list of outstanding work, but ensures that it can always be viewed for reference if necessary. - **[Option B]** Delete the WO Request. This will permanently remove it from the system, which is ideal for duplicates and other erroneous requests that are no longer needed.	[WO Request, Status] Rejected [WO Request, Function] Delete
2.12 Send feedback to requester automatically	Inform the person who requested the work that their proposal has been rejected, and explain why. When the rejection has been confirmed in the CMMS (either via a specific "Rejected" Status, or via deletion of the request, as per the options above in step 2.11) the CMMS should automatically request feedback via a pop-up window, which is then sent to the requester via email (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017).	Prompt feedback is essential for explaining why the request was rejected, in order to build respect for the emergent work process and to encourage users to continue to report defects with high quality information in the future. If requests are "ignored" then users will disengage with the process and begin to request work via other channels, which will undermine the MD process (Anonymous Expert 2, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017).	[WO Request, Field] Rejection Feedback [WO Request, Function] Rejection Feedback Field to become mandatory when Status = Rejected or WO Request Deleted (depending on option selected in step 2.11) [WO Request, Function] Email contents of Rejection Feedback Field to Requester when Status = Rejected or WO Request Deleted (depending on option selected in step 2.11)

Process Step	Definition	Justification	CMMS Implementation Spec.
2.13 Confirm Approval	If the request is approved, then action must be taken in the CMMS to demonstrate this and remove it from the list of outstanding requests (Monsanto, 2007; Duffuaa and Raouf, 2015).	- **[Option A]** Use a specific WO Request Status to flag the approved work – e.g. "Approved". This method provides a clear indicator within the CMMS that the request has already been screened (i.e. by using the Status field). - **[Option B]** Do nothing. Shortly, in step 2.17, a WO will be created, linked to the WO Request. This will provide an alternative indicator within the CMMS that the request has already been screened (i.e. the "Associated WO" field within the WO Request will NOT be blank). Note however, that this means that step 2.17 must take place during screening, not after, as indicated on the flowchart (see step 2.17 for more details). These two options just provide subtly different ways of filtering out requests that have already been screened, so that they are not screened twice. It is just a matter of preference.	[WO Request, Status] Approved [WO Request, Field] Associated WO [WO Request, Function] Associated WO field automatically populated when a WO is created via a WO Request.
2.14 Agree Priority	An appropriate Priority classification is agreed for the work, which determines its Due Date (Suttell, 2005; Monsanto, 2007; Hickman, 2011; US Department of the Army, 2013; Al-Turki et al., 2014). The requester's initial Priority suggestion is taken into consideration and amended accordingly (Institute of Nuclear Power Operations, 2010).	Emergent Work must be ranked according to urgency, so that the most critical tasks are scheduled first (British Standards Institute, 2004; Sahoo, 2008; Modi, 2010; Ismail, 2014). Without clear priority definitions, complete with a range of corresponding due dates, it is difficult to address defects in a timely manner – which leads to long MTTR (Mean Time to Repair) scores and an increasing backlog of incomplete work (Anonymous Expert 3, 2017; Anonymous Expert 7, 2017; Anonymous Expert 10, 2017). Accurate and consistent prioritisation is vital for managing emergent work effectively with limited resources. The screening authority must question and scrutinise each request and ensure that the correct priority decisions are made, to avoid the development of an unmanageable backlog (see step 2.20) (Anonymous Expert 11, 2017). There are two commonly used methods for Emergent Work prioritisation: - **[Option A]** A linear Priority scale is used with approximately 5 levels (variable, depending on user preference) – the most appropriate priority is simply selected in each case based on the perceived urgency of the task (e.g. Immediate, Urgent, Normal, Minor) (Monsanto, 2007; Hickman, 2011; Institute of Nuclear Power Operations, 2010; Modi, 2010; Al-Turki et al., 2014; Ismail, 2014). - **[Option B]** A decision matrix or grid is utilised, typically with 2 axes depicting "impact of failure" and "probable time until failure", which are multiplied together to determine an appropriate Priority Score (Institute of Nuclear Power Operations, 2010; Fernandez and Marquez, 2012; US Department of the Army, 2013; Peters, 2014; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017). Option B is useful for ensuring consistent and objective priority decisions, which is helpful in contexts where there is an established culture of poor prioritisation decisions (i.e. "my problem is more important than yours") (Anonymous Expert 1, 2017; Anonymous Expert 4, 2017; Anonymous Expert 8, 2017). However, this method is more time consuming to use than Option A (i.e. 2 axes need to be considered and discussed as opposed to 1), and can therefore slow the screening process down; sensible priorities can be achieved using Option A if a small, experienced and consistent screening team make all of the decisions (e.g. Operations and Maintenance supervisor) (Peters, 2014; Anonymous Expert 6, 2017).	[WO Request, Field] Priority, Due Date [WO Request, Function] Due Date adjusted automatically based on Priority selection.

Process Step	Definition	Justification	CMMS Implementation Spec.
2.15 [Optional] Add Task to STO Holding List	If the task in question will require a STO (Shutdown / Turnaround / Outage) to enable execution, then it is allocated to the STO Holding List. Review of this list and assignment to a specific STO event is done at a later stage as part of a (separate) STO planning process (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017).	STO management takes place over a longer timescale, using a different business process which cannot be wholly incorporated into this one (which is designed for day-to-day maintenance). A STO planning process mixes in some project management principles, e.g. critical path and networking. The STO build-up and scope definition process is also different – tasks need to be planned much longer in advance (Anonymous Expert 12, 2017). For sites where STO maintenance takes place, it is essential to clearly identify any tasks that require a STO event, so that they can be grouped together into a STO work scope (Howard, 2004; Campbell and Reyes-Picknell, 2006; Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Hickman, 2011; Peters, 2014). Common methods for flagging STO work within the CMMS include utilising a specific Priority classification (Monsanto, 2007; Anonymous Expert 9, 2017) or Work Team (Anonymous Expert 8, 2017).	Create Priority Classification = STO Create Work Team = STO [WO Request, Field] Assigned STO Event
2.16 Assign Responsible Planner	An appropriate person is assigned responsibility for planning the WO (Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 12, 2017).	There are two different methods available: - **[Option A]** A named individual should be assigned to each task – this provides clear ownership and accountability to a single person, to ensure that the task will be progressed in a timely manner (Anonymous Expert 5, 2017). It also allows any follow up questions to the directed to the correct person more easily (Anonymous Expert 6, 2017). - **[Option B]** In some contexts, it is not always appropriate or possible to assign responsibility to an individual person (e.g. in contexts where planners work shifts) – in such cases it is acceptable to assign planning responsibility to a planning group or discipline-specific team instead (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017).	[WO Request, Field] Responsible Planner

Process Step	Definition	Justification	CMMS Implementation Spec.
2.17 Create Work Order	A WO is created for the approved task – now that the scope, priority and responsible planner have been agreed. This will enable the task to move forward into planning, scheduling and execution. The WO will be linked to the associated WO Request for reference, and will contain come of the same basic information – plus additional planning and cost details. Although this step is a key output of the Screening Process, the actual creation of the WO should take place afterwards, to save the time of the various stakeholders present. Once they have made a decision, it is acceptable to just set the WO Request status to "Approved", and let a planner create the WO outside of the screening meeting (however, this only applies if Option A is selected in step 2.13; Option B relies on a WO being created within the Screening Process to confirm the approval of the request).	An approved WO is the output of the screening process; it will be used to manage the task through the next stages of planning, scheduling and execution (Howard, 2004; Suttell, 2005; Institute of Nuclear Power Operations, 2010; Peters, 2014; Ramskill, 2014; Duffuaa and Raouf, 2015). There are 3 options available with respect to the relationship between WOs and WO Requests: - **[Option A]** A new WO is created for each and every approved WO Request. Each task has 1 WO Request representing the "problem" (e.g. defect, failure), and one corresponding WO representing and managing the "solution" (i.e. the work to be carried out to resolve the defect / failure). This provides a clear, direct link between the two entities (Anonymous Expert 11, 2017). - **[Option B]** Multiple WO Requests per WO, i.e. many requests (problems) are grouped together onto a single WO, to be resolved together. This is useful in contexts where assets are spread over a large geographical area, and a single person or team is assigned to execute multiple tasks which are taking place in a similar location at a similar time. The advantage is that the work is grouped together into a single package to simplify the assignment process and reduce the admin burden during WO closure. Individual WO Requests are still retained for each defect / failure in order to record and quantify them as separate "problems", but the cost and resource data for the overall "solution" is managed via a single WO (Anonymous Expert 11, 2017). - **[Option C]** Do not use WO Requests at all. As described earlier in step 2.04, there is an option to completely omit WO Requests from the MD process. In such cases, the WO Request information will already held within the WO – they are in effect a single entity, meaning that a direct 1-2-1 relationship is the only option. It is important that the Criticality rating of the asset is clearly visible within any WO Requests or WOs raised against that asset. This information is essential during work prioritisation, to highlight the importance of the work and the potential consequences if it is not carried out on time (e.g. a breach of legal compliance or potential plant breakdown) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).	[WO, Fields] Asset Record ID, Problem Description, Priority, Responsible Planner [WO, Function] Only permit creation if WO Request Status = Approved [WO, Field] Associated WO Request(s) [WO Request, Field] Asset Criticality = (copied from Asset Record)
	A note on WO numbering (not shown on flowchart because this is a one-off implementation consideration):	There are two options available with respect to WO numbering formats: - **[Option A]** The WO is automatically assigned the next number in a sequence (within a defined number range). This method ensures that every WO has a unique ID number, which is essential. - **[Option B]** WO numbers are coded so that each character has a defined meaning, i.e. they conform to a specific pattern depending on certain characteristics (e.g. the first character represents WO Type, where 1 = Corrective Maintenance, 2 = Preventive Maintenance, etc.). This provides useful information about the WO at a glance, e.g. WO Type, location, discipline (Anonymous Expert 7, 2017).	[WO, Field] WO Number = sequentially generated within a defined number range [WO, Field] WO Number = coded according to pre-defined WO parameters.

Process Step	Definition	Justification	CMMS Implementation Spec.
2.18 [Optional] Define WO Type	It is common practice to categorise WOs based on the type of activity undertaken – using a "WO Type" field – so that these activities can be quantified and compared (e.g. to compare the cost or hours of reactive work in comparison to preventive work) (Anonymous Expert 1, 2017).	The following WO Type options are available; use any combination, depending on what needs to be measured and compared in the given context: - Corrective / Reactive Maintenance (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017) - Time Based / Preventive Maintenance (Anonymous Expert 8, 2017) - Condition Based Intervention / Predictive Maintenance (Anonymous Expert 1, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017) - Condition Assessment / Monitoring / Inspection (Anonymous Expert 9, 2017) - Project / Modification (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 9, 2017) - Root Cause Analysis (RCA) / Improvement time (Anonymous Expert 9, 2017) - Admin / Non-maintenance time (Anonymous Expert 9, 2017)	[WO, Field] WO Type = (Various, depending on user selection)
2.19 Default WO Status = "Awaiting Planning"	New WOs have the default status "Awaiting Planning".	So that planners can easily identify all newly approved WOs that require their attention (Hickman, 2011; Ismail, 2014; Duffuaa and Raouf, 2015).	[WO, Status] Awaiting Planning (default)
2.20 [Optional] Review Emergent Work Backlog	All Emergent Work that is approved but not yet executed is considered to be in "backlog" (Peters, 2014; Rødseth and Schjølberg, 2017; Shiver, 2017). It is important to periodically monitor the size and scope of this list, and to re-prioritise work if conditions change (note that it is possible to measure the backlog size in hours or in terms of the quantity of WOs).	The size of the Emergent Work Backlog is a critical measure of system control: If the quantity of outstanding work is increasing significantly over time (either in relation to number of tasks or number of man-hours of work), this shows that the MD process is failing – assets are accumulating defects at a faster rate than the system can respond to them (Anonymous Expert 1, 2017; Anonymous Expert 4, 2017). The cause could either be a lack of resources, the inefficient use of them (ultimately due to poor MD process design), or a failure to investigate and address the root causes of recurring defects (Jackson, 2016) – this will be discussed in framework section 6.	[CMMS, Function] Search for and list out WOs by Status [CMMS, Function] Sum total of listed WOs (by quantity or planned hours)
2.21 Notify Production Supervisor	On discovering a high priority failure, the requester promptly informs the Production Supervisor / Shift Manager by phone or PA system (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	If something has occurred which significantly impacts the plant or process, then the person responsible for that process must be made aware so that key decisions can be taken: 1. Confirm that the situation is indeed High Priority (Anonymous Expert 11, 2017) 2. Determine the best course of action to minimise the consequences	N/A
2.22 Notify Maintenance Supervisor	When aware of a high priority failure / breakdown, the Production Supervisor / Shift Manager promptly informs the appropriate Maintenance Supervisor by phone or PA system (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	Because they possess the expertise required to manage urgent / critical plant breakdowns in the most effective manner, and hence minimise the consequences. They are also well placed to assess the nature of the breakdown and judge who should be called upon to help form a plan of action.	N/A
2.23 Assemble Reactive Response team	Call an emergency meeting with the relevant experts, dependant on the nature of the breakdown (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	A diverse team with a broad range of skills will allow the most effective plan of action to be developed, i.e. representatives from Production, Maintenance, Planning, and SHEQ as appropriate.	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
2.24 Develop a plan of action	Determine the steps necessary to rectify the issue as quickly and safely as possible (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	A plan of action needs to be developed and implemented promptly to minimise the consequences of the breakdown.	N/A
2.25 High Priority Emergent Work Strategy	High Priority Emergent Work includes failures that need to be addressed more urgently (e.g. a critical asset failure resulting in a production stop or a safety / environmental / legal risk). There are two alternative approaches for the screening, planning and scheduling of such tasks: - **[Option A]** Screening, Planning and Scheduling is Fast-tracked - **[Option B]** Bypass Screening, Planning and Scheduling; Proceed directly to Execution Arguments for each option are presented in the next column.	- **[Option A]** No work should ever go ahead without a WO – no matter how urgent the task (Monsanto, 2007; US Department of the Army, 2013; Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017). This is the only way to ensure that every single task is properly screened and checked before going ahead and consuming limited labour resources, which need to be used wisely to address agreed priorities (Anonymous Expert 5, 2017; Anonymous Expert 11, 2017). If any work is allowed to bypass the screening process – even urgent or High Priority work – then it undermines the entire process because resources are not carrying out the work that was agreed, which ultimately results in poor maintenance performance (US Department of the Army, 2013; Shafeek, 2014). A WO also enables the task to be planned and scheduled effectively, and provides a record of work history (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017). However, High Priority tasks should not have to wait for the next screening meeting (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017); they can be "fast-tracked" through the screening and approval process (Suttell, 2005; Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Peters, 2014). The Production and Maintenance Supervisors will already be present and aware of the situation (from the previous 4 steps), and they have the authority to approve the WO Request immediately without waiting for the next screening meeting. The creation of the WO and the subsequent planning activities, can be carried out by a dedicated planner so that it does not "slow down" the execution effort (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017). These dedicated planners can also ensure that any potential opportunistic maintenance is included alongside the High Priority work (which will usually require an emergency plant shutdown) (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017). - **[Option B]** With High Priority work, resolving the problem as quickly as possible is more important than CMMS admin – in some contexts an immediate response is necessary because there is a fatality risk (e.g. power loss to a hospital); the WO can be created afterwards to save time (Hickman, 2011; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).	N/A

Table 11 – Framework Section 2 commentary table – Emergent Work Request & Screening

8.3. *Framework Prefix Section*

It was recognised in the problem definition (see section 5.3.4) that in order for effective performance measurement to be possible, the end user's CMMS must be configured in alignment with their specific KPI (Key Performance Indicator) requirements – i.e. with suitable input fields to capture the source data required for each report. And because the end user's specific KPI requirements will be different in each case, it was recognised that the framework would need to be flexible enough to adapt to any potential KPI combination, and provide a fully compatible CMMS implementation specification for any case. Additionally, for certain KPIs, it was recognised that specific business process steps are required to ensure that the required data is actually collected in practice as an integrated part of day-to-day maintenance processing – and therefore the framework would also need to take this into account. Therefore an extensive list of possible maintenance KPIs is also included in the framework, complete with a thorough definition and a list of references for each KPI (see Appendix D). CMMS implementation requirements have been developed for each KPI, specifying the input fields required for data capture. Additionally, against each KPI is a list of the mandatory business process steps that will be required to ensure that the relevant data can be collected in practice. This will allow the end user of the framework to locate their own pre-existing KPIs from the list, and understand the impact that this will have on their tailoring options within the framework. Consequently, this KPI selection feature is located in a prefix section of the framework, as it must be carried out as one of the first phases in the tailoring process (i.e. because KPI choices influence the rest of the framework design). An extract from this KPI selection feature is presented below in Table 12 to demonstrate this process. The full list is available in Appendix D.

	Performance Measure	Definition	Mandatory CMMS Implementation Requirements	Mandatory Framework Steps	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Ellis, 1998	Fernandez and Marquez, 2012	Institute of Nuclear Power Operations, 2010	Kidam and Hurme, 2013	Kumar et al., 2013	Modi, 2010	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Seela and Yackel, 2017	Shafeek, 2014	Simões, Gomes and Yasin, 2011	Trindade and Nathan, 2008	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
1	**Assets classed as Critical**	Assets with class = critical / Total assets	[Asset Record, Field] Criticality = Critical	1.09											■															
2	**Assets that have routine maintenance in place**	Assets that are included in a Routine Maintenance Call / Total assets	[Routine Maintenance Call, Field] Asset Record ID	1.19					■						■															
3	**Data completeness**	Asset record number of mandatory fields populated / Required	[Asset Record, Function] Ability to flag fields as mandatory	1.07											■															
4	**Availability loss due to failure**	Hours of plant downtime incurred, if caused by plant failure	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown	5.40 2.04				■	■					■	■						■		■					■		
5	**Availability loss, critical equipment only**	Hours of plant downtime incurred, if Asset Class = Critical	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown [WO Request, Field] Asset Record ID [Asset Record, Field] Criticality = Critical	5.40 2.04 2.04 1.09									■																	
6	**Backlog - Average age**	Average time since creation for all outstanding WO Requests	[WO Request, Function] Date, Time created [WO Request, Status] Problem Resolved	2.04 5.41												■														
7	**Backlog - Rate of change**	New WO Requests created - WO Requests Closed in time period	[WO Request, Status] New Request [WO Request, Status] Problem Resolved	2.05 5.41		■									■						■									
8	**Backlog - Total**	Quantity of WO Requests outstanding (i.e. not complete)	[WO Request, Status] Problem Resolved	5.41	■	■						■	■		■	■					■	■	■					■	■	
9	**Defects discovered via preventative inspection**	Quantity of WO Requests with Type = Inspection Based	[WO Request, Field] WO Request Type = Inspection Based	5.36											■															
10	**MTBF or MTTF or reliability**	Operating time period / Quantity of WO Requests created with "Type = Breakdown" during time period	[WO Request, Field] WO Request Type = Breakdown [WO Request, Function] Date, Time created	2.04 2.04		■		■	■		■	■	■		■			■		■	■	■	■					■		
11	**MTTR**	Total downtime incurred / Quantity of breakdowns	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown	5.40 2.04		■		■	■	■	■	■			■			■		■	■	■	■		■			■		
12	**Defect Priority Distribution**	Quantity of WO Requests, categorised by Priority	[WO Request, Field] Priority	2.14															■					■						
13	**Quantity of defects by system**	Quantity of WO Requests, categorised by System / Location	[WO Request, Field] System or Location	2.04, 1.05										■													■			
14	**Quantity of defects by asset type**	Quantity of WO Requests, categorised by asset type	[WO Request, Field] Asset Type	2.04, 1.09										■			■													
15	**Quantity of defects by root cause**	Quantity of WO Requests, categorised by root cause	[WO Request, Field] Root Cause	5.40										■					■					■						
16	**Number of deferred Routines**	Quantity of WO Requests with Type = Deferral Request	[WO Request, Field] WO Request Type = Deferral Request	4.07												■														
17	**Quantity of breakdowns**	Quantity of WO Requests with Type = Breakdown	[WO Request, Field] WO Request Type = Breakdown	2.04		■					■	■								■										
18	**Repeated maintenance tasks due to poor quality**	Quantity of WO Requests with Type = Rework	[WO Request, Field] WO Request Type = Rework	5.25		■														■			■					■		
19	**Historical average task duration**	Actual time taken to complete a given task, on average	[WO, Field] Actual Duration = (hours)	5.30											■													■		
20	**Cost of labour**	WO Actual Duration * Labour rate for Work Team	[WO, Field] Actual Duration = (hours) [Work Team, Field] Labour Rate = (£)	5.3							■	■	■		■			■			■		■							

Table 12 – Extract from Framework Prefix section showing a selection of possible maintenance KPIs and their impact on the framework tailoring process

8.4. *Conclusion*

Framework v2 was successfully developed by applying 176 industry-based improvement suggestions (that were elicited via a modified Delphi study as described in section 7) to the initial literature-based design. This is the final version of the framework and the main deliverable of this research (see Appendix D for the complete framework). The next section of this report (i.e. section 9) will document the implementation and testing of the framework in the sponsor company, and discuss the impact that this had on the problem that was defined in section 5.

Aside from the 176 improvements derived from the Delphi study, the following notable differences exist between Framework v1 and v2:

- All optional practices are now more visually apparent (i.e. listed as option A / B / C etc.).
- The terminology in general is less manufacturing-focused (the author's bias unintentionally excluded infrastructure contexts in some cases in v1).
- All "red practices" have been validated by the addition of references from industry.
- The first two sub-sections of the framework have been merged together as a result of an improvement suggestion elicited from industry experts during the Delphi study. This was because both sections cover prerequisites for new asset registration and they have several interdependencies.
- There is a great deal more content, particularly in the commentary tables which have been significantly expanded and improved based on expert guidance from industry.
- Numerous small changes have been made to the structure and layout to improve clarity.

8.4.1. Innovations

As mentioned above, all "red practices" from Framework v1 were validated by the addition of references from industry – 21 practices in total. These practices were added directly by the author because they were known to be practiced in industry (based on the author's 10 years' experience as a maintenance professional), yet references could not be found in the literature despite an extensive search. Now that these additional 21 practices have been verified with a reference from industry, this research is able to add to the body of knowledge. Although the execution of these practices in industry is not novel, their inclusion in a published framework or model is novel – a fact that adds to the innovative nature of the framework.

The main innovation claim for this project is of course the successful development of the framework itself. This delivers several key innovations that were anticipated earlier in section 5.3.1:

1. The framework facilitates the development of a fully tailored (parametric) business process for MD. It contains options from multiple different industries and sectors (sourced from both the literature and from industry), enabling the end user to consider practices from a wide range of sources in order to develop an effective MD process to suit any context. A generic, universal framework that can be useful in many different industries is unique, because existing MD processes are generally designed for a single, specific case and do not take into account different contexts. The feedback received so far from industry professionals (see section 7.5.1) has validated the potential benefits of the framework and its prospective application in industry.

2. The ability of the framework to generate a fully aligned implementation specification for the supporting CMMS, which is also tailored according to the same contextual requirements – is also highly innovative, as it combines a tailored business process design tool with a software specification tool to solve a common industry problem (i.e. poor alignment between the MD process and the supporting CMMS). This enables the end user of the framework to not only create a tailored MD process, but it also ensures that they are able to purchase, implement and configure a CMMS that has the necessary capabilities to fully support that process.

3. The framework covers multiple AM subject areas that are not normally combined, via a single, holistic solution that takes the subject of MD beyond its existing boundaries. i.e.:
    - the planning and control of maintenance activities
    - the configuration and implementation of supporting CMMS software
    - the utilisation of outsourced labour to deliver maintenance
    - the measurement of maintenance performance
    - the management of corrective actions in the event of failure
    - the root cause analysis of failures to drive improvement

- the collation of improvement opportunities and the execution of improvement initiatives
- the determination of maintenance requirements via analytical methods
- parts acquisition and supply to the point of use
- The execution of STO activities.

4. The framework also contains 3 minor innovations (as discussed already in section 7.5.1), all related to additional CMMS functionality that can be achieved through creative software configuration. These practices were considered "minor" innovations because although there were proven to be novel, they were only found to be beneficial in a limited number of contexts (i.e. typically contexts that had very mature CMMS processes – those with basic systems did not appreciate the benefit).

8.4.2. Further Work

The framework as presented currently is a very complex document that presents a large volume of information (i.e. a series of large flowcharts covering 157 core process steps, 109 contextual options, and 30,000+ words of guidance). It is undoubtedly useful material that has the potential to improve MD practices in real industrial contexts (this will be proven via implementation in the sponsor company in the next section of this report) – however it is potentially quite difficult to read and navigate for the end user, due to the sheer volume of information. Ease of use would be greatly improved if the framework was developed further into perhaps a software package or even a mobile app that could take the end user through the tailoring process step-by-step, clearly presenting each option and the relevant supporting information, and automatically building up the tailored business process and CMMS implementation specification in the background as decisions are made. This would be the next step for turning what is currently a series of flowcharts and tables into a usable product.

To be successful, such a software package would have to be designed with user-friendliness in mind, breaking the decision process down into manageable chunks. This could be achieved by presenting one framework step at a time, providing clear introductory information (i.e. definitions, purpose, and the overall concept of the step) and visually highlighting any relationships with other related steps within the framework. Each contextual option would then be clearly presented via a side-by-side comparison, clearly explaining the of the pros and cons, with perhaps examples or case studies available from different industries. The end user would then simply read the material (or watch / listen, as appropriate), make a decision, and then click on their selection. The software would then automatically adapt the process flowchart and present this to provide a clear visual overview of the selection made and the impact on the overall MD process design. The software would also build up the CMMS implementation specification in the background based on the selections made, resulting in a file that is ready to use as part of an IT project scope. At the end of the tailoring process, the software would enable the end user to simply print out (or render electronically) their finished MD process flowcharts and CMMS specification to a professional standard. The software could also collect and provide statistics based on data gathered from other end users in the maintenance community (e.g. the most common options selected in each industry sector). This shared knowledge, along with feedback collected from end users (e.g. suggested improvements to the framework), would enable the further development and expansion of the framework over time as more industrial users give their input.

Such a software package would be highly useful in industry and could potentially have commercial value, as it could be sold to businesses as an alternative to hiring a business process consultant. Unfortunately there will not be any scope for carrying out such work as part of this project (this is after all an industrial engineering project, not a software development project), but it could be interesting to pursue afterwards.

9. Implementation in the Sponsor Company and Assessment of Impact on the Defined Problem

This section will describe the work undertaken to address ROs 4 and 5, as defined in section 5.1.6. Looking back to the beginning of section 5, the initial reasoning behind the development of the framework was to resolve a number of significant gaps that were found in the sponsor's AMS. After the final version of the framework had been successfully developed, the next project goal was to implement and test the framework in the sponsor company, in order to demonstrate that it could successfully close the gaps in the sponsor's AMS that were identified in the Problem Definition. This section will describe the methodology and results of this assessment.

9.1. *Implementation Strategy*

One of the key findings of the literature review that was carried out as part of the Problem Definition (see section 5.3.1), was that the functionality of the CMMS / ERP system is a key enabler for any MD process – i.e. without the required supporting IT functionality, a MD process can never be implemented to its full extent (see section 5.3.1). Therefore, it was recognised that the implementation of the framework in the sponsor company would need to conform to this logic – i.e. beginning with an upgrade of the supporting CMMS / ERP system (hereafter referred to as implementation phase 1), and then following with an implementation of a new MD process at the sites (hereafter referred to as implementation phase 2).

It was also recognised that both of these phases would require a significant amount of time to complete. Phase 1 would constitute a global IT project (because the sponsor utilised a single, shared ERP system across the group – a system called SAP) involving the selection and procurement of additional software functionality, complete with configuration, testing and user training etc. Phase 2 would involve significant change management at the sites, to enable the introduction of new MD practices and work processes. And unfortunately, the necessity for these two phases to occur sequentially, rather than in parallel, would only add to the time-pressure. Therefore, in order to complete both implementation phases prior to the end of this research project, it was decided to start as early as possible with phase 1, i.e. immediately following the initial framework design (i.e. Framework v1). This had the obvious disadvantage that the CMMS / ERP upgrade would be based on v1 of the framework, but this was considered to be the best option in order to achieve some meaningful change to the sponsor's MD practices within the time available. Therefore, some of the events described in this section, particularly regarding implementation phase 1, actually took place in parallel to the development of Framework v2, as shown in Fig.1 below.

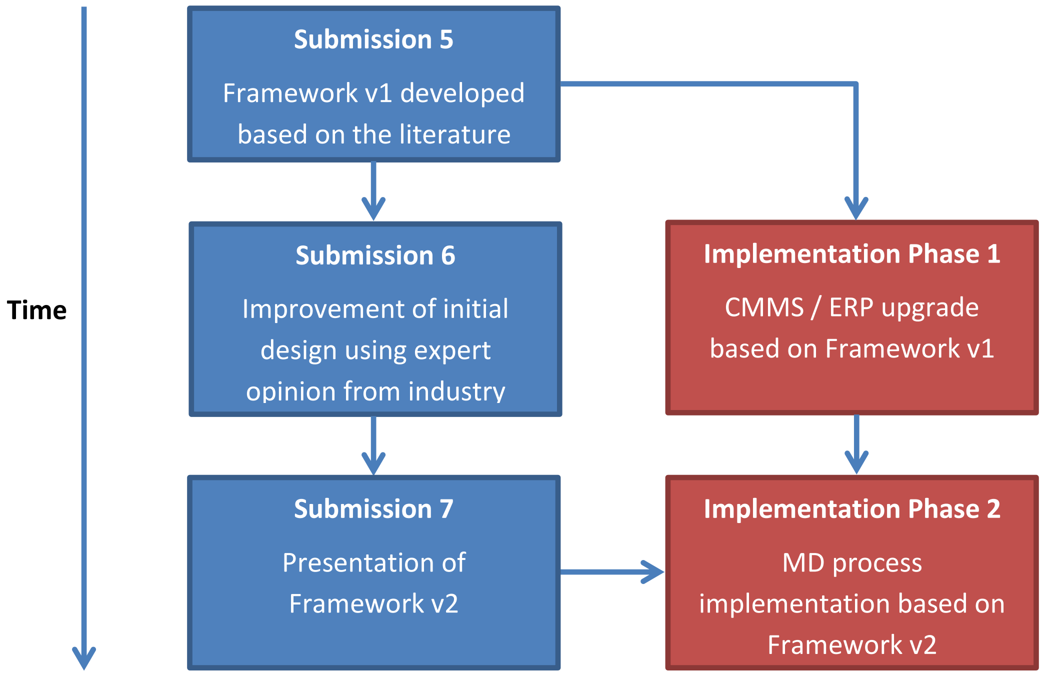


Fig. 11 – Implementation phases in relation to framework development timescale.

9.2. *Pre-implementation Phase*

This section describes the early preparation activities that took place prior to implementation phase 1.

9.2.1. Obtaining agreement from the business to proceed with the implementation

The sponsor company holds a group-wide Maintenance Manager's Meeting (MMM) up to 3 times per year, whereby the Maintenance Managers from each of the company's 5 sites meet to discuss best practice, share experience, and agree common approaches and strategies for maintenance. As the Maintenance Manager at the company's newest site, the author is a regular attendee at this meeting and was able to successfully use it as a platform to obtain support for the implementation and testing of the framework across the business.

Framework v1 was presented at the MMM in June 2015. The Maintenance Managers were also shown the results of the assessment carried out on their existing AMS (as documented in section 4 of this report), in order to demonstrate the extent of the problems found and to build a strong case for the framework's implementation. At the time, the business had recently appointed a new global Head of Maintenance who recognised the need for improvement across the group, and was fortunately very open to change. He considered this project to be a positive opportunity, and recognised the potential it had to deliver improvements to group's MD practices. Therefore, a decision was made to adopt Framework v1 as a replacement for the business's existing global MD process.

It is clear that this was an early success for the project, in that strong backing was obtained from a senior figure to proceed with the implementation. However, it was not an absolute success, in that the manner of the framework's adoption was somewhat distorted from the way that the author intended. As discussed in section 5.1.4, a key observation that led to the development of the framework in the first place, was that multi-site "one-size-fits-all" MD processes are not effective – because they lack the flexibility needed to suit local contexts. It should be immediately clear that by adopting the framework as the "Global Maintenance Process v2.0", the MMM group had directly contradicted the spirit of the framework. It would have been better to reject the "global process" concept altogether, and instead implement a series of independent, tailored processes at each site. This argument was conveyed to the business at the time, but there was a strong reluctance to let go of a deep-seated, ingrained practice of employing *global* business processes with common, aligned practices at all sites. Furthermore, the company directors had firmly mandated this approach for all business areas, and it was not within the power of the MMM group to deviate from this (misguided) instruction.

A compromise was eventually reached however, which is represented diagrammatically in Fig. 12 below. The business would retain an aligned "global process" document – which would essentially be derived from Framework v1 by removing all options that could never foreseeably apply to any of the sponsor's sites, and by adjusting some of the terminology to match that of the business and its current ERP system, SAP (see rows 1 and 2 in Fig. 12). This "global process" would then be subjected to further tailoring in order to develop 5 "local processes" suited to each of the sponsor's 5 sites (i.e. rows 3 to 7 in Fig. 12). This was, in the author's view, a slightly wasteful approach, and would not be recommended for other businesses. However, it was necessary in order to satisfy the cultural expectations of the sponsor and the demands of senior management. This approach did actually have one benefit in that it would streamline and simplify the tailoring process at the "local" level, because all of the non-applicable content would already have been removed at the "global" level. Fig. 12 below demonstrates this agreed tailoring process diagrammatically – note that it is only a representation and is not to scale.

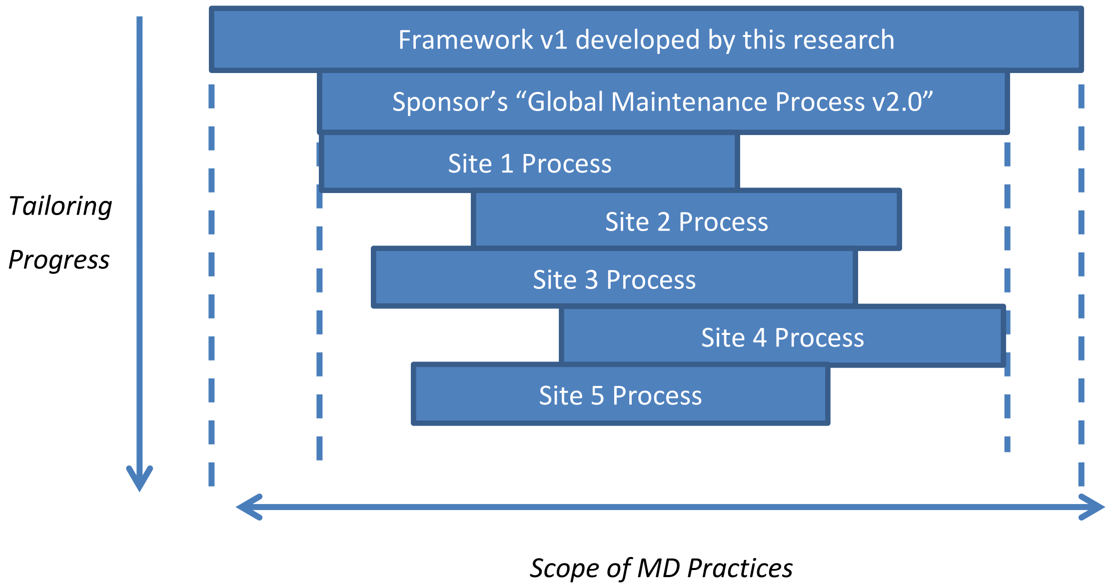


Fig. 12 – Representation of the tailoring process agreed with the business

The proposed implementation plan (shown earlier in Fig. 11) was discussed with the MMM group; specifically the intention to begin with a CMMS / ERP upgrade project (i.e. implementation phase 1). However, before this upgrade could take place, a CMMS implementation specification would be required to define the requirements for the project. Therefore it was agreed that the tailoring process shown above in Fig. 12 should be executed first – as a paper-exercise only – in order to produce a series of local processes and matching local CMMS implementation specifications based on Framework v1. These specifications could then be utilised as an input for the CMMS / ERP upgrade in implementation phase 1.

9.2.2. Utilisation of Framework v1 to develop the sponsor's "Global Maintenance Process v2.0"

Recall from earlier in section 5.3.4, that the selection of Key Performance Indicators (KPIs) was identified as an essential first step in MD process design. This is because each KPI has a corresponding MD process step and supporting CMMS functionality that must be implemented to enable the source data to be captured. Consequently, a KPI selection feature was incorporated into the prefix section of the framework (as discussed earlier in section 6.1.3), enabling the end user to select their desired KPIs and fully understand the impact that their selections will have on the framework tailoring process (see Appendix D). Therefore the first stage in the new "global process" design was to agree on which performance measures should be made available within the sponsor company (globally-aligned measures were preferred by the group to enable a comparison in performance between the sites).

A working group was established with expertise in KPIs (led by the author), with a stakeholder present from each site (Catt, 2015d). The group drafted a recommendation of suitable performance measures for the business, using the KPI selection tool from the framework prefix section, which was subsequently reviewed and approved by the Maintenance Managers. Table 13 below shows the outcome of this review, i.e. the list of KPIs that were selected, along with the corresponding framework steps and CMMS implementation requirements that consequently became mandatory during the subsequent tailoring process.

	Performance Measure	Definition	CMMS Implementation Requirements	Mandatory Framework Steps	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Ellis, 1998	Fernandez and Marquez, 2012	Institute of Nuclear Power Operations, 2010	Kidam and Hurme, 2013	Kumar et al., 2013	Modi, 2010	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Seela and Yackel, 2017	Shafeek, 2014	Simões, Gomes and Yasin, 2011	Trindade and Nathan, 2008	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
7	**Backlog - Rate of change**	New WO Requests created - WO Requests Closed in time period	[WO Request, Status] New Request [WO Request, Status] Problem Resolved	3.05 6.37		■									■						■									
8	**Backlog - Total**	Quantity of WO Requests outstanding (i.e. not complete)	[WO Request, Status] Problem Resolved	6.37	■	■						■	■		■	■					■	■	■					■	■	
9	**Defects discovered via preventative inspection**	Quantity of WO Requests with Type = Inspection Based	[WO Request, Field] WO Request Type = Inspection Based	6.32											■															
10	**MTBF or MTTF or reliability**	Operating time period / Quantity of WO Requests created with Type = Breakdown in time period	[WO Request, Field] WO Request Type = Breakdown [WO Request, Function] Date stamp	3.04		■		■	■		■	■	■		■			■		■	■	■	■					■		
11	**MTTR**	Total downtime incurred / Quantity of breakdowns	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown	6.36 3.04		■		■	■	■	■	■			■			■		■	■	■	■		■			■		
12	**Defect Priority Distribution**	Quantity of WO Requests, categorised by Priority	[WO Request, Field] Priority	3.12															■					■						
13	**Quantity of defects by system**	Quantity of WO Requests, categorised by System / Location	[WO Request, Field] System or Location	1.03, 3.04										■													■			
14	**Quantity of defects by asset**	Quantity of WO Requests, categorised by asset type	[WO Request, Field] Asset Type	1.05, 3.04										■			■													
15	**Quantity of defects by root**	Quantity of WO Requests, categorised by root cause	[WO Request, Field] Root Cause	6.36										■					■					■						
27	**Labour utilisation**	Total time recorded against completed WOs / Total time available, per Work Team, per Period	[WO, Field] Actual Time Taken = (hours) [Work Team, Field] Type = (various) [Work Team, Function] Define working calendar	6.28 4.05		■		■	■		■	■	■		■			■			■	■				■		■		
31	**Planned Vs Actual task duration**	Estimated task duration against Actual recorded time	[WO, Field] Planned Duration = (hours) [WO, Field] Actual Duration = (hours)	4.06 6.28		■		■				■						■				■			■			■		
32	**Ratio of Reactive to Preventative work**	Quantity of completed WOs when WO Type = Reactive, compared to when WO Type = Routine	[WO, Field] WO Type = Routine [WO, Field] WO Type = Reactive [WO, Status] Work Complete	4.14 3.15 6.33	■	■					■	■	■		■	■		■			■	■	■		■				■	
35	**Schedule delays caused by operations preparation activities**	Quantify schedule delays per WO (Actual recorded time - Planned time), filtered by Reason for delay = Ops Prep	[WO, Field] Planned Duration = (hours) [WO, Field] Actual Duration = (hours) [WO, Field] Delay Code = Ops Prep [WO, Function] Delay Code field to become mandatory if Actual Duration exceeds Planned Duration (by tolerance)	4.06 6.28 6.28												■												■		
39	**WO status distribution**	Quantify the number of WOs at each WO Status	[WO, Status] Various, User defined	3.16								■										■								
42	**WOs executed on time**	% of WOs where WO Status = Work Complete, and Completion Date does not exceed Due Date, within defined time period	[WO, Status] Work Complete [WO, Field] Due Date = (date) [WO, Field] Completion Date = (date) [WO, Function] Automatically record Completion Date when WO Status is changed to Work Complete	6.33 4.14 6.33				■			■	■	■		■	■		■			■	■			■			■		
43	**WOs initiated via inspection**	Quantify WOs which we raised as a result of an inspection, i.e. if WO Type = Condition Based	[WO, Field] WO Type = Condition Based	3.15							■	■													■					

Table 13 – KPIs selected for use by the Sponsor Company, developed using the Prefix section of Framework v1

Once the above KPI requirements were established, work could begin on the design of the sponsor's new business process. The author led a workshop at the next MMM in October 2015, utilising Framework v1 to design the "Global Maintenance Process v2.0". As indicated above in section 9.2.1, the aim was to remove all content from Framework v1 that could never feasibly be applied to any of the sponsor's sites, and to adjust the terminology to match that of the business and its pre-existing CMMS / ERP system (i.e. SAP).

The outcome of this workshop was a list of decisions regarding each of the framework's optional practices, including the reasons for rejection or acceptance where applicable – a selection of example decisions from this list are shown below in Table 14.

Framework v1 Optional Practice	**Decision made for the Sponsor's new "Global Maintenance Process v2.0"**
1.04 If asset is movable / interchangeable ensure each individual item is serialised	Include as a mandatory practice – serialised assets are already in use; functionality to be retained.
3.13 If STO maintenance is required, specify which event to include the work in	Include as an optional practice – some sites require STO (Shutdown / Turnaround / Outage) maintenance; some do not.
4.04 Who carries out detailed planning? (i.e. Technician or Planner)	Include both options – each site has different organisational structures and job roles.
4.23 Goods Issue to WO via RFID (Radio-frequency Identification)	Include as an optional practice – RFID is not currently in use at any site for materials management, but would be a beneficial addition.
5.06 Due Date Deferral Process	Include as a mandatory practice – all sites operate in highly regulated environments where this process is already mandated by law.
5.09 Fully integrate Maintenance and Production schedules	Exclude this option – all plants operate continuously and produce a single product; there is no "production schedule".

Table 14 – Example tailoring decisions made during the development of the sponsor's "Global Maintenance Process v2.0" using Framework v1.

This list of decisions (illustrated by the example shown above in Table 14) was utilised by the author to develop the sponsor's new "Global Maintenance Process v2.0", which was subsequently drafted, reviewed, and then published internally as a formal business process in Nov 2015 (Catt, 2015e).

9.3. *Implementation Phase 1 – CMMS / ERP Upgrade*

As discussed earlier in section 9.2.1, the Maintenance Managers agreed to subject the new Global Maintenance Process v2.0 to further tailoring at each site, in order to deliver a series of fully detailed and flexible solutions for each locality. The responsibility to carry out this local tailoring was assigned to each site's Maintenance Manager, who had the authority and knowledge to select and implement the most suitable framework options for their own context (with the assistance of the author if so desired). Due to the time constraints of the project (as discussed earlier in section 9.1), the sites were advised to focus initially on the framework steps directly related to CMMS functionality, in order to produce their CMMS implementation specifications first, so that they could be utilised during implementation phase 1.

The result was 5 local CMMS implementation specifications; extracts from these specifications are shown in the example below (i.e. Table 15), which displays them side-by-side to illustrate the tailoring differences between sites. Note that the default specification as defined in the sponsor's "Global Maintenance Process v2.0" is also shown for reference in column 2 (i.e. Global), with the subsequent columns showing the local requirements for each site. Recall that the format for the framework configuration specification was defined earlier in section 8.2.

Generally speaking, many of the requirements for the 4 older sites were quite similar (i.e. Sites 1 – 4), because they had historically shared a common MD process and CMMS / ERP platform, with identical functionality employed at each site, and they were all culturally very resistant to any deviation from their existing position. By contrast, the author's site (i.e. Site 5), with a new-build facility, was starting from a "blank page" and was therefore more able to consider new ideas.

A gap analysis was then conducted (by the author) by comparing the CMMS implementation requirements from each site with the capabilities of the sponsor's pre-existing CMMS / ERP system (i.e. SAP). A total of 60 CMMS functionality requirements were identified that the sponsor's existing CMMS platform was unable to provide – and these items were subsequently used to provide a clear scope for implementation phase 1. An excerpt from this analysis is shown in Table 15 below, in the final column, to provide some examples of the typical functionality that was missing.

Framework v1 Step	CMMS Imp. Spec. (Global)	CMMS Imp. Spec. (Site 1)	CMMS Imp. Spec. (Site 2)	CMMS Imp. Spec. (Site 3)	CMMS Imp. Spec. (Site 4)	CMMS Imp. Spec. (Site 5)	Gap Analysis
3.09 Change WO Request Status = "Rejected"	[WO Request, Status] Rejected	[WO Request, Status] Rejected	[WO Request, Status] Rejected	[WO Request, Status] Rejected	[WO Request, Status] Rejected	[WO Request, Status] Rejected	Additional WO Request status required ("Rejected"), not available in current SAP build.
3.10 Send feedback to requester automatically	[WO Request, Field] Feedback [WO Request, Function] Feedback Field to become mandatory when Status = Rejected [WO Request, Function] Email contents of Feedback Field to Requester when Status = Rejected	Functionality not desired.	Functionality not desired.	Functionality not desired.	Functionality not desired.	[WO Request, Field] Feedback [WO Request, Function] Feedback Field to become mandatory when Status = Rejected [WO Request, Function] Email contents of Feedback Field to Requester when Status = Rejected	Requirement for automated email to be sent to requester when status is changed to "Rejected".
3.13 If STO maintenance is required, specify which event to include the work in	[WO Request, Field] Priority = STO [WO Request, Field] STO Event = User Defined [WO Request, Function] If Priority = STO, STO Event Field becomes mandatory	[WO Request, Field] Priority = STO [WO Request, Field] STO Event = User Defined [WO Request, Function] If Priority = STO, STO Event Field becomes mandatory	[WO Request, Field] Priority = STO [WO Request, Field] STO Event = User Defined [WO Request, Function] If Priority = STO, STO Event Field becomes mandatory	Functionality not desired.	Functionality not desired.	[WO Request, Field] Priority = STO [WO Request, Field] STO Event = User Defined [WO Request, Function] If Priority = STO, STO Event Field becomes mandatory	Additional STO Priority option required. STO Event field to become mandatory if Priority = STO
4.18 Availability Check	[WO, Function] Check stock levels of specified materials against required quantities	[WO, Function] Check stock levels of specified materials against required quantities	[WO, Function] Check stock levels of specified materials against required quantities	[WO, Function] Check stock levels of specified materials against required quantities	[WO, Function] Check stock levels of specified materials against required quantities	[WO, Function] Check stock levels of specified materials against required quantities	Standard SAP functionality, but not currently functioning – investigation & fix required
4.21 Generate Pick List	[WO, Function] Generate Pick List	[WO, Function] Generate Pick List	[WO, Function] Generate Pick List	[WO, Function] Generate Pick List	[WO, Function] Generate Pick List	[WO, Function] Generate Pick List	Functionality available as standard in SAP but not currently activated.
4.23 Goods Issue to WO	[Material, Function] Goods Issue to WO [Material, Function] Goods Issue via RFID	[Material, Function] Goods Issue to WO	[Material, Function] Goods Issue to WO	[Material, Function] Goods Issue to WO	[Material, Function] Goods Issue to WO	[Material, Function] Goods Issue to WO [Material, Function] Goods Issue via RFID	Enable RFID input for Goods Issue – standard SAP functionality will require enhancement with new user interface
4.31 Review parts on order and expedite if necessary	[PO, Function] Provide visibility of orders where delivery dates are passed without a goods receipt	Functionality not desired	Functionality not desired	Functionality not desired	Functionality not desired	[PO, Function] Provide visibility of orders where delivery dates are passed without a goods receipt	New functionality required to monitor related PO status and associated delivery information – not available as standard with current CMMS package (SAP).

Framework v1 Step	CMMS Imp. Spec. (Global)	CMMS Imp. Spec. (Site 1)	CMMS Imp. Spec. (Site 2)	CMMS Imp. Spec. (Site 3)	CMMS Imp. Spec. (Site 4)	CMMS Imp. Spec. (Site 5)	Gap Analysis
5.14 Assign named individuals to each task	[WO, Field] Job Step Assignment = (individual) [Graphical Scheduler, Function] View and adjust WO Job Step Assignments	[WO, Field] Job Step Assignment = (individual) [Graphical Scheduler, Function] View and adjust WO Job Step Assignments	[WO, Field] Job Step Assignment = (individual) [Graphical Scheduler, Function] View and adjust WO Job Step Assignments	[WO, Field] Job Step Assignment = (individual) [Graphical Scheduler, Function] View and adjust WO Job Step Assignments	Functionality not desired	[WO, Field] Job Step Assignment = (individual) [Graphical Scheduler, Function] View and adjust WO Job Step Assignments	New functionality required to enable graphical scheduling – not available as standard with current CMMS package (SAP).
6.06 Issue & Accept Permit before starting work	[WO, Function] Electronic Permit to Work	[WO, Function] Electronic Permit to Work	Functionality not desired	[WO, Function] Electronic Permit to Work	Functionality not desired	Functionality not desired	New functionality required to enable electronic permits – not available as standard with current CMMS package (SAP).
6.28 Confirm Actual Duration	[WO, Field] Actual Duration = (hours) [WO, Field] Delay Code [WO, Function] Delay Code becomes mandatory if Actual Duration > Planned Duration (by a tolerance)	[WO, Field] Actual Duration = (hours)	[WO, Field] Actual Duration = (hours)	[WO, Field] Actual Duration = (hours)	[WO, Field] Actual Duration = (hours)	[WO, Field] Actual Duration = (hours) [WO, Field] Delay Code [WO, Function] Delay Code becomes mandatory if Actual Duration > Planned Duration (by a tolerance)	New WO Field required for Delay Code. Field to become mandatory if Actual duration > Planned duration (with adjustable tolerance).
6.31 Record any observations or condition monitoring readings if taken	[WO, Field] Condition Value = (qualitative or quantitative) [WO, Field] Condition Units = (variable depending on user requirements)	Functionality not desired	Functionality not desired	Functionality not desired	Functionality not desired	[WO, Field] Condition Value = (qualitative or quantitative) [WO, Field] Condition Units = (variable depending on user requirements)	Functionality available as standard in SAP but not currently activated.
7.04 Generate KPI Reports via the CMMS	Ability to generate and display the KPIs shown in Table 13	Ability to generate and display the KPIs shown in Table 13	Ability to generate and display the KPIs shown in Table 13	Ability to generate and display the KPIs shown in Table 13	Ability to generate and display the KPIs shown in Table 13	Ability to generate and display the KPIs shown in Table 13	New functionality required to enable KPI reporting and analysis – not available as standard with current CMMS package (SAP).
7.06 Create WO Request (Type = Improvement)	[WO Request, Type] Improvement [WO Request, Field] Owner	Functionality not desired	Functionality not desired	Functionality not desired	Functionality not desired	[WO Request, Type] Improvement [WO Request, Field] Owner	Additional WO Request Type required for Site 5 only ("Improvement").

Table 15 – Comparison of CMMS Implementation Specifications produced for each of the sponsor's sites using Framework v1, complete with Gap Analysis for Implementation Phase 1

9.3.1. From Gap Analysis to Formal Project Scope

A large number of the identified gaps required only relatively minor changes, such as the addition of new fields, field options, or the activation of standard functionality that was not currently in use. The sponsor's existing CMMS programme – SAP – was fairly flexible and such changes could be executed relatively easily and cheaply via the use of their in-house IT contractor; therefore these were grouped together into a single configuration scope for the project. However, 6 more significant gaps were identified that could not be addressed without the procurement of additional software, because they required features that were not available as standard within SAP (see Table 16 below).

Significant Gap	Framework v1 Step Reference
Adjust WO planned duration automatically based on historical average.	**4.06** Estimate the duration of each Job Step
Review and update BOM (Bill of Materials) during WO planning.	**4.08** Review & update Asset spare parts list / BOM
Monitor related PO status and associated delivery information	**4.30** Confirm Order and Delivery Date **4.31** Review parts on order and expedite if necessary
Graphical scheduling	**5.01** Review all Routine Plans **5.06** Propose a start date & allocate resources **5.06** Resource availability information required **5.12** Calculate Schedule Loading **5.14** Assign named individuals to each task **6.01** Ensure Published Schedule is visible and accessible **6.20** Update Maintenance Schedule to reflect changes
Electronic permits	**6.06** Issue & Accept Permit before starting work **6.26** Hand plant back to Operations
KPI reporting	**7.01** Review failure data and identify significant or recurring problems / opportunities for improvement **7.03** Performance data collected automatically via the CMMS **7.04** Generate KPI Reports via the CMMS

Table 16 – Significant gaps in the sponsor's CMMS functionality

Each of these gaps would require more significant investment to address – relative to the other identified gaps – therefore due to limited funding they had to be prioritised. The MMM group determined that the most significant gap was graphical scheduling (because the entirety of framework section 5 and parts of section 6 depend on this functionality), followed by KPI reporting (because one cannot measure and improve performance without KPIs). It was decided that the other 4 gaps were less urgent, and could therefore be addressed later, outside of the scope of this project.

9.3.2. The procurement of additional SAP functionality

Potential suppliers of graphical scheduling and KPI software were approached in order to find a suitable solution. Detailed functionality requirements were derived from Framework v1, specifically by utilising the commentary tables for all process steps related to Graphical Scheduling and KPI reporting (as listed above in Table 16), and by utilising the Framework prefix section that focuses on CMMS functionality (see Appendix D). See Table 17 below for a full specification of requirements.

Category	Functionality Requirement
1) Graphical Scheduling	Provides a graphical scheduling interface, with a Gantt chart layout
	Ability to view WO list, Gantt schedule, and resource capacity panes from a single screen
	Ability to “drag and drop” Work Orders, start times, and finish times
	Ability to "drag and drop" individuals onto WOs to assign them to the task.
	Ability to add scheduling relationships and display these visually
	Any changes on the schedule result in real time automatic updates to the WO dates
	Ability to filter and sort WO selection by any criteria e.g. User Status, Order Type, Work Centre etc.
	Ability to double click on any WO on the schedule to open up and view the WO details
	Ability to provide visual indication of WO due dates, i.e. milestones.
	Ability to provide visual indication of WO-related material availability / estimated delivery dates
	Ability to visualise WO progress, i.e. % complete
	Capacity pane to display total work allocated against total available hours per work centre (i.e. schedule loading). With visual indication / colour-coding to show if the resource is over / under allocated.
	Capacity pane – ability to expand work centres to show the same capacity details as above but per individual
	Absence / leave data visible from within the schedule tool
	Ability to auto level the schedule based on available capacity and scheduling relationships, and calculate critical path
	Supports a variety of date range types / cycles (e.g. 5 week months)
	Ability to display / communicate published schedule to wider team
	Ability to manage routine maintenance plans graphically. Ability to see upcoming calls in the Gantt chart view, and delay / skip calls as required
2) KPI Reporting	Ability to produce KPI graphs / charts within SAP, using data that is collected automatically
	Facilitates troubleshooting and Root cause analysis, i.e. drill down into the data
	Ability to automatically generate and email reports to multiple recipients (as a .pdf) at specified frequencies
	Reports show real time data - reports are instantly available, no overnight batching

Table 17 – Functional requirements for Graphical Scheduling and KPI Reporting software

After some initial research using the web, it was clear that two principal types of solution were available that could meet the requirements listed above in Table 17, whilst being compatible with SAP. The first consisted of separate, external programmes that could receive SAP data, manipulate it in order to generate either a schedule or suite of KPI reports, and then (in the case of the scheduler) send the data back to SAP to update the live WOs (hereafter referred to as an "external solution"). The second option involved enhancing the SAP programme itself, by adding scheduling and KPI functionality directly into the existing SAP system (hereafter referred to as an "integrated solution"). The preference was to opt for an integrated solution, because transporting data to an external software package is a time-consuming batch process (usually carried out overnight), and data becomes out of date the moment it leaves SAP (i.e. any changes to the native data in SAP after the batch is taken are omitted from the schedule or KPI report). An integrated solution by contrast is always using live data that is completely up to date, because everything is within a single cohesive system. The main downside of an integrated solution is that they generally have an inferior "look and feel" because they are restricted to using SAP's relatively poor standard graphics. This is more important than it sounds – recall from section 7.5.2 that one of the findings from discussions with industry experts was that *ease of use* is a significant factor in the success of CMMS implementations. Numerous steps in the MD process make use of the schedule to visually communicate work assignments to various team members (see Appendix D), and if the schedule is not comfortable and clear to read, then this could lead to a negative experience for end users, and ultimately hostility towards the MD process. Similarly, if KPI reports are not visually appealing and easy to read, then this also has a negative effect on their usability.

Only two suppliers could be found that were able to offer an integrated solution for SAP (note that company names have been anonymised in this report). A formal Request for Information (RFQ) was sent to both suppliers via the sponsor's procurement department, which included the functionality requirements shown above in Table 17. The scope of the request included pricing for 60 users (including 20 with "full" access and 40 with "read-only" access, based on the sponsor's requirements), plus all associated implementation and support costs.

Both suppliers responded to the RFQ with full quotations and offers to demonstrate their respective solutions. These demonstrations were attended by the author, who then assessed each solution to determine the most suitable offer, based on 3 criteria:

1. The ability to meet the minimum functional requirements from the specification in Table 17;
2. Any additional features that went beyond the minimum requirements;
3. Pricing competitiveness.

After analysing both offers, the results were shared with the MMM group and a supplier was selected. This was a relatively simple decision because one supplier performed better against all 3 selection criteria: as well as being more competitive on price, their offer also included numerous additional features that went above and beyond those required by the minimum specification in Table 17. The majority of these features did not offer new functionality per se, but instead made significant improvements to the existing user interface, enabling existing functionality to be utilised in a simpler and more user-friendly manner (which as discussed earlier is a significant factor in the success of any CMMS implementation). One of these additional improvements also solved one of the significant gaps from Table 16 at no extra cost (i.e. "Review and update BOM during WO planning").

9.3.3. Obtaining funding for the project

As discussed in section 9.3.1, the majority of the gaps that were identified in the sponsor's CMMS could be resolved relatively easily and at low cost by the sponsor's in-house IT contractor. These items were absorbed into an already-planned SAP project (covering other functional areas as well as maintenance), therefore funding did not have to be obtained. However, the additional scheduling and KPI functionality that was required to solve the more significant gaps was not included in this budget, therefore a business case had to be developed by the author in order to obtain additional funding (Catt, 2016). The principle arguments of this business case are summarised below in Table 18:

	Benefit	Measure/KPI	Value (€'000)
A	Improved resource utilisation	30 minutes improved Wrench Time per technician per day (i.e. time spent actually doing maintenance)	€700k per year
B	Less reactive work	Reduction in reactive maintenance from 60% to 55% on average	€675k per year

Table 18 – Summary of benefits claimed in the Graphical Scheduling / KPI business case

Further explanation for these benefits was also provided in Catt (2016), as follows:

- **(A)** Through more effective planning and scheduling, existing maintenance technician resources can be more fully utilised so that more work is executed per day. Each technician is estimated to achieve an extra 30-60 minutes of useful work per day ("wrench time"), based on evidence from the supplier's existing customers. Even taking the most conservative estimate of 30 minutes, when multiplied over a year (assuming 260 working days) across all sites (assuming a total of 180 technicians at a rate of ~€30/hour) this gives a significant efficiency saving through a reduction in wasted labour *(i.e. €30 x 0.5 x 260 x 180 = €700,000).*
- **(B)** When technicians have more time available for maintenance, then the backlog of outstanding defects will reduce – defects which would previously have been ignored now get resolved because more time is available to address them. Therefore these defects do not get the opportunity to progress into full equipment failures – and this creates savings because reactive work (i.e. repairing equipment that has *already* failed) is more expensive when compared to other types of maintenance (it also carries a greater risk to production and safety). At [Sponsor Company], on average 60% of all maintenance carried out is reactive work (and up to 80% at some sites) due to poor maintenance practices. Improved planning and scheduling functionality will make an important contribution to improving this figure – if we target an improvement in our % reactive KPI from 60% to a very safe target of 55% as a result of this project, this would save €675k per year in maintenance costs across the business. See the following calculation (note that WO quantity and cost data has been extracted directly from SAP):
    - *Average number of WOs per year across all sites = 28,800*
    - *Average cost of a reactive WO (i.e. Order Type "PM1") = €470*
    - *Reactive work total costs at 60% = 28,800 x 0.6 x €470 = €8,121,000*
    - *Reactive work total costs at 55% = 28,800 x 0.55 x €470 = €7,444,800*
    - *Difference = €676,200*

The following soft (i.e. non-financial) benefits were also included in the business case (Catt, 2016):

- Will provide essential CMMS functionality that was found to be missing from standard SAP during a recent gap analysis;

- Will Improve data relevance and timeliness due to the integrated nature of the scheduling solution;
- Will improve communication and visibility of upcoming maintenance work, which reduces the risk of missing regulatory inspections;
- Will reduce end-user frustration by providing a simpler user interface for several core SAP functions.

The business case also detailed the expected costs for the entire project in full (Catt, 2016), as summarised below in Table 19:

	Expense	Cost Estimate
External Project Costs	Software licensing costs (based on RFQ response)	€439,217
	User training (20 days, split across all sites)	€36,400
Internal Project Costs	IT Project Manager fees	€50,000
	IT Implementation Manager fees	€30,000
	In-house IT contractor fees (implementation support)	€10,000
Other	Contingency (10% of initial investment)	€56,560
	Total Initial Investment	**€622,177**
Ongoing Costs	Annual service fees (20% of license cost)	€87,843

Table 19 – Estimated project costs from the Graphical Scheduling / KPI business case

Based on the estimated costs and benefits of the project (as shown above in Figs. 29 and 30), the following financial analysis was conducted (Catt, 2016):

- A simple payback calculation to show the number of years it would take for the investment to pay off.
- A Return on Investment (ROI) calculation to show the efficiency of the investment, i.e. a ratio of the net profit (over the software's expected 10 year life) over the initial investment cost.
- A Net Present Value (NPV) calculation to take into account "the time value of money" – i.e. each year's net profit was discounted to reflect the return that could be earned if the money was invested elsewhere (at an 8% discount rate, as dictated by the sponsor's finance department).

These calculations are summarised in Table 20 on the next page.

The completed business case was presented to the sponsor's IT director and Finance director in order to obtain approval for the funding, which was subsequently granted. Permission was obtained to go ahead with the implementation in Jan 2016.

Proposed Project Title:		**SAP Graphical Scheduling / KPI**										
Proposed Project Owner:		**Phil Catt**										
Proposed Start Date:		Jan-16					**Estimated Project Useful Life:**			10	years	
Proposed Target Operational Date:												
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
		€'000	€'000	€'000	€'000	€'000	€'000	€'000	€'000	€'000	€'000	€'000
Costs												
	Project (External)	-476	0	0	0	0	0	0	0	0	0	0
	Project (Internal)	-90	0	0	0	0	0	0	0	0	0	0
	On-going	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88
	Contingency (10%)	-57	0	0	0	0	0	0	0	0	0	0
Benefits												
	One-off	0	0	0	0	0	0	0	0	0	0	0
	On-going	0	1,375	1,375	1,375	1,375	1,375	1,375	1,375	1,375	1,375	1,375
	Other	0	0	0	0	0	0	0	0	0	0	0
Net cash flows		**-622**	**1,287**	**1,287**	**1,287**	**1,287**	**1,287**	**1,287**	**1,287**	**1,287**	**1,287**	**1,287**
Cumulative net cash flow		-622	665	1,952	3,239	4,526	5,814	7,101	8,388	9,675	10,962	12,249
Discount rate		8%			**ROI**	**816%**						
NPV		**8,015**			**Payback**	**1**	**years**					

Table 20 – Financial Analysis from the Graphical Scheduling / KPI business case

9.3.4. Implementing the new functionality

Unfortunately – for reasons outside of the control of this project – a decision was made by the sponsor's IT department to merge the scope of this project (including the Graphical Scheduling / KPI functionality implementation) into a pre-existing SAP project covering multiple business functions (this project was already mentioned earlier in section 9.3.3), which was scheduled to be carried out from October – December 2016. This decision was taken due to IT resource limitations (i.e. the availability of IT contractors, project managers, acceptance testers etc.), and consequently this caused a delay of almost 12 months between project approval and actual "go-live" of the new functionality. However, this delay did not have a significant impact on this EngD project because the time was used to prepare for phase 2 of the implementation (i.e. the new MD process implementation) – and for the formal write-up of various EngD portfolio submissions.

During the Oct – Dec 2016 group IT project, the author was involved as the business lead for maintenance with the following responsibilities:

- Main point of contact during solution development, to ensure that any configuration decisions were aligned to the specification in Table 15.
- Lead role during User Acceptance Testing – ensuring that the final build contained all functionality required, and that the final look and feel was acceptable for end users.
- Arrangement and coordination of training for all end users (delivered by the supplier).
- Configuration of all KPI reports to ensure that the requirements of Table 13 were met.

9.4. *Implementation Phase 2 – new MD process based on Framework v2*

As explained earlier in section 9.1 (and illustrated by Fig. 11), the second phase of the implementation utilised Framework v2, which was developed in parallel to implementation phase 1. The aim of phase 2 was to utilise the final framework design to implement new MD processes at each of the sponsor's sites, building on the foundation of the improved CMMS functionality introduced in phase 1.

Consider that phase 2 differs from phase 1, in terms of the nature of the challenges involved. Whilst introducing new IT functionality certainly has its difficulties (e.g. producing a detailed specification, obtaining funding and resources, managing a global IT project), implementing a new business process is arguably more difficult because it involves a significant change to the existing way of working for a large number of people. This introduces many organisational change management issues – e.g. identifying key influencing groups and obtaining their support, managing people who are perhaps resistant to change, promoting and communicating change effectively etc. (Reeves and Horvath, 2018). Such efforts, although valid and potentially interesting, are time-consuming and ultimately not part of the scope of this research (this is after all a maintenance delivery study – not a change management study), and therefore attempts were made to minimise their effect on this implementation. Perhaps an appropriate piece of future work would be to study how to effectively introduce a new MD process to an existing environment (rather than how to design an effective MD process, which is the aim of this research).

Therefore, in order to eliminate these change management issues as much as possible, and to concentrate purely on demonstrating that the framework can be successfully utilised to design and implement an effective MD process that is tailored to suit a specific context (i.e. the central innovation claim of this project) – it was decided to carry out phase 2 at the author's site only (hereafter referred to as "Site 5"), rather than at all of the sponsor's sites. This is because Site 5 consisted of a new-build facility, with an entirely new workforce (see section 2.1 of this report). It consequently had no existing MD processes or systems, and therefore there would be fewer change management implications (admittedly, new employees could still have expectations and preconceptions about MD based on their previous experiences, but it was assumed that since they had recently moved to a new workplace, they would fully expect to encounter change and would therefore be less resistant to it). Also, as the Maintenance Manager for the new site, the author of this project had full control over the specific MD processes to be implemented, and so there would be fewer barriers to the introduction of new practices. Although this approach resulted in a smaller scope than it could otherwise have been (i.e. 1 site as opposed to 5), it still provided a significant enough example to demonstrate that the framework can be successfully utilised in practice, and to ultimately fill the gaps originally identified in the Problem Definition (see section 5 of this report).

9.4.1. MD process design for Site 5 using Framework v2

Framework v2 was utilised to design a new MD process for Site 5, in order to fully test the framework tailoring process. This exercise was led by the author, with input from other local maintenance colleagues with appropriate MD expertise, in order to reach a consensus on the best decisions for the site. The tailoring process (i.e. making selections from the framework's optional practices) is demonstrated below in Table 21, which focuses on framework section 2 (i.e. Emergent Work Request and Screening) – i.e. the same section that was presented earlier in section 8.2 of this report (when reading Table 21, please refer to section 8.2 for a full definition of each framework step, if necessary).

The final column in Table 21 makes reference to implementation phase 1 (i.e. the CMMS upgrade project that was documented in section 9.3 of this report), by highlighting any associated CMMS functionality that was delivered in the earlier phase of this project. In each case, the practices in question would not have been possible without the supporting CMMS functionality – which demonstrates the effectiveness of the CMMS implementation specification produced by the framework (another central innovation claim of this research). Note that where the final column is blank, this means that standard SAP functionality already offered sufficient support, and therefore no changes were required in phase 1.

Notice that many of the decisions made for framework section 2 (catalogued in Table 21) revolve around the following aspects of site 5's context:

- A maintenance-intensive plant with a large volume of emergent work
- A lean organisation structure with a small workforce
- A nuclear site with significant safety and security considerations

These contextual factors have significantly shaped the Emergent Work screening process that has been designed for site 5, based on framework section 2. This demonstrates the central innovation claim of this research – i.e. that the framework is fully tailorable and can produce an MD process that is aligned to the context of the asset in question.

Following on from Table 21 is a selection of evidence that demonstrates that an Emergent Work screening process has genuinely been implemented at Site 5, utilising framework section 2 and the decisions made in Table 21.

Framework Step	Options Available	Option selected at Site 5 (with reason)	Phase 1 Reference
2.02 Determine Appropriate Course of Action	**[Optional]** – In some contexts, tasks that take less than 30 minutes to execute may be permitted to completely bypass the normal screening process and proceed directly to execution (i.e. "quick fixes"). No WO is required; technicians can go ahead and resolve them autonomously.	Option not selected – the preference at Site 5 was to screen 100% of work requests, regardless of their complexity. This ensures that all work entering the MD process has been formally agreed and prioritised before (finite) resources are allocated to it.	
2.03 [Optional] Attach Defect Tag	A hand-written tag is physically attached to the failed asset.	Option selected – in the context of Site 5 the benefits of using defect tags was thought to outweigh the disadvantages listed in the framework commentary (for reference see section 8.2 for a full description of the advantages and disadvantages). Particularly of interest was the safety benefit in providing a clear visual indication of exactly which asset the technician should be maintaining, to prevent accidental exposure to live equipment. Also considered useful was the tag's ability to prevent duplicate WO requests. The disadvantage of perishability in outdoor environments does not apply at Site 5, which is wholly contained within a secure building (as are all nuclear plants for security reasons). Also, the potential negative effects on customer perception do not apply to because customers are not permitted in plant areas for safety reasons.	
2.04 Create WO Request	Regarding who creates WO Requests in the CMMS: - **[Option A]** Requester creates their own WO Request - **[Option B]** Requester calls help desk to create WO Request on their behalf	Option A selected – in Site 5's context, all requesters will be highly skilled plant operators, who will be able to provide full details regarding the nature of each problem. This is best captured first hand to ensure high quality information, rather than via an unskilled administrator. As discussed in the full framework commentary section 8.2, an administrator / help desk approach is more appropriate in contexts where requests are made by non-technical persons (e.g. members of the public, passengers, tenants etc.).	
	[Optional] Cost Estimate. In contexts where maintenance execution is entirely outsourced, a cost estimate or quotation is required because cost is often the most significant factor in the approval decision.	Option not selected – work approval is driven by production or legal compliance demands in the vast majority of cases, rather than by cost (maintenance is executed by a fixed quantity of company employees, rather than a flexible pool of contractors).	
	[Optional] Geospatial mapping data. Coordinates are entered to pinpoint the defect location; this functionality may only be applicable in contexts with large civil structures (e.g. a runway) or where assets are spread over a large geographical area.	Option not selected – the plant is a centralised chemical / nuclear plant with a relatively small geographical footprint and multiple stories (up to 4 in most areas), making GPS (Global Positioning System) mapping impractical. There is also poor GPS signal due to the concrete radiation shielding installed in many plant areas.	
	[Optional] The WO Request is created via a mobile device that interfaces with the CMMS, rather than from a fixed computer terminal. This does not alter the content of this step, only the end-user experience. Additional CMMS functionality will be required to enable this optional feature.	Option not selected – as stated in the framework commentary, this functionality does not alter the MD process in any way; it only changes the end user experience. The user completes the same actions, only on a tablet computer instead of a desktop computer. The benefits of doing so in a centralised plant with a small geographical footprint (like Site 5) are less significant than in a large infrastructure business with significant travel time between the job site and the desk. Therefore this functionality was considered a low priority for the site. It will potentially be explored as further work in the future.	

Framework Step	Options Available	Option selected at Site 5 (with reason)	Phase 1 Reference
	[Optional] Completely omit WO Requests from the MD Process. Instead, directly create a WO at step 2.04, with a "New Request" Status, and simply review this during the screening meeting.	Option not selected – as discussed in the framework commentary in section 8.2, this approach is only suitable in contexts where the CMMS package is able to provide a WO with all of the same fields and functionality that are available in a WO Request. The following WO Request functionality is not available within a WO in SAP (i.e. the CMMS software used at the site), so this is not a practical option: • the ability to define request types (see step 2.04) • the ability to record failure codes (see step 5.40) • the ability to record detailed failure history and technician comments (see step 5.35) • the ability to assign multiple requests to a single WO (see step 2.17, Option B)	
2.06 [Optional] Pre-Screening Quality Check	If the Screening Process consists of a routine meeting with multiple stakeholders (i.e. Option A below), it may be appropriate to carry out a preliminary quality check on all new WO Requests prior to the screening meeting.	Option selected – Site 5 is expected to be very maintenance intensive once the plant is operational, with a significant quantity of defects arising each day. Therefore in this context a pre-screening step will be useful for improving the quality of information within WO Requests, prior to the screening meeting.	
2.07 Review outstanding requests	With regards to the methodology used for the Screening Process, the following options are available: • **[Option A]** Routine meeting with multiple stakeholders • **[Option B]** Single screening role (i.e. interdepartmental coordinator) • **[Option C]** Client / customer screening	Option A selected – the site falls firmly into the manufacturing context as described in the framework commentary; there are multiple stakeholders from different departments who need to engage in screening decisions.	
2.09 [Optional] WO Request Status = "Awaiting Information"	If it is not possible to determine the full scope of work during screening without further investigation, the WO Request should be added to a holding list using the status "Awaiting Information". Responsibility should be assigned to someone during the screening meeting to investigate and return with clarification.	Option not selected – this particular function was included in Framework v2 only, therefore the sponsor's CMMS does not support it (because phase 1 was based on Framework v1). However, this will not cause a significant problem in the context of Site 5: if any WO Requests do require further information, they can simply remain at the "New Request" status, where they will be discussed at each subsequent screening meeting until further clarification has been obtained.	
2.11 Confirm Rejection	If the request is rejected, then action must be taken in the CMMS to demonstrate this and remove it from the list of outstanding requests: - **[Option A]** Use a specific Status to flag the rejected work – e.g. "Rejected". - **[Option B]** Delete the WO Request.	Option A selected – The preference at Site 5 was to reject via a status change rather than a deletion. This ensures that rejected requests are still available for analysis if required – e.g. to trend the quantity of rejections per month, or the individuals with the most rejections (i.e. to highlight training requirements).	New WO Request Statuses were added in phase 1 to support this decision.
2.13 Confirm Approval	If the request is approved, then action must be taken in the CMMS to demonstrate this and remove it from the list of outstanding requests: - **[Option A]** Use a specific WO Request Status to flag the approved work – e.g. "Approved". - **[Option B]** Do nothing. Shortly, in step 2.17, a WO will be created, linked to the WO Request. This will provide an alternative indicator within the CMMS that the request has already been screened (i.e. the "Associated WO" field within the WO Request will NOT be blank).	Option A selected – mostly for consistency with the decision above for step 2.11. Also, this choice means that step 2.17 (i.e. WO creation) can take place after the screening meeting, rather than during it, to save the time of the stakeholders present.	New WO Request Statuses were added in phase 1 to support this decision.

Framework Step	Options Available	Option selected at Site 5 (with reason)	Phase 1 Reference
2.14 Agree Priority	An appropriate Priority classification is agreed for the work, which determines its Due Date: - **[Option A]** A linear Priority scale is used with approximately 5 levels (variable, depending on user preference) - **[Option B]** A decision matrix or grid is utilised, typically with 2 axes depicting "impact of failure" and "time until failure", which are multiplied together to determine an appropriate Priority Score	Option A selected – as indicated in the framework commentary (see section 8.2), option B would be too time-consuming in Site 5's context, because it is expected to be a very maintenance-intensive facility with many WO requests to discuss at each screening meeting. Sensible priorities will be achieved faster using option A, because the screening team will be composed of a small, experienced and consistent group (i.e. the Operations and Maintenance supervisors, with a planner present to facilitate).	A new linear priority scale was added to the site's WO Requests to support this decision.
2.15 [Optional] Add Task to STO Holding List	If the task in question will require a STO (Shutdown / Turnaround / Outage) to enable execution, then it is allocated to the STO Holding List. Review of this list and assignment to a specific STO event is done at a later stage as part of a (separate) STO planning process.	Option selected – Site 5 will undertake multiple STO events each year, therefore this is essential functionality. A specific Priority classification will be utilised within each WO or WO Request to identify STO-related work.	The priority option "Shutdown" was included in the site's linear priority scale to support this decision.
2.16 Assign Responsible Planner	An appropriate person is assigned responsibility for planning the WO: - **[Option A]** A named individual is assigned to each task - **[Option B]** assign a planning group or discipline-specific team	Option A selected – Site 5's organisation structure has been designed to be very lean with a small workforce (there are currently only 2 planners), so in this context an individual name is the most appropriate way to clarify ownership of each task.	
2.17 Create Work Order	There are 3 options available with respect to the relationship between WOs and WO Requests: - **[Option A]** A new WO is created for each and every approved WO Request - **[Option B]** Multiple WO Requests per WO - **[Option C]** Do not use WO Requests at all.	Option A selected – As discussed above (see step 2.04), option C is only suitable in contexts where the CMMS package is able to provide a WO with all of the same fields and functionality that are available in a WO Request; this is not the case at Site 5. And as discussed in the framework commentary (see section 8.2), option B is designed for contexts in which assets are spread over a large geographical area, and a single person or team is assigned to execute multiple tasks that are taking place in a similar location at a similar time (which is also not relevant in this case). In the context of Site 5, option A provides a clear one-to-one link between the "problem" (i.e. the WO Request) and the "solution" (i.e. the WO to be carried out to resolve the defect / failure).	
	Decision regarding WO numbering: - **[Option A]** The WO is automatically assigned the next number in a sequence (within a defined number range). - **[Option B]** WO numbers are coded so that each character has a defined meaning, i.e. they conform to a specific pattern depending on certain characteristics (e.g. the first character represents WO Type, where 1 = Corrective Maintenance, 2 = Preventive Maintenance, etc.).	Option A selected – the functionality described in option B was included in Framework v2 only, therefore the sponsor's CMMS does not support it (because phase 1 was based on Framework v1). Option B would have been beneficial in Site 5's context (because it provides useful information about each WO at a glance), but its absence is not a significant loss – it does not fundamentally alter the MD process flow, it is just a small time saver.	
2.18 [Optional] Define WO Type	The following WO Type options are available; use any combination, depending on what needs to be measured and compared in the given context: - Corrective / Reactive Maintenance - Time Based / Preventive Maintenance - Condition Based Intervention / Predictive Maintenance - Condition Assessment / Monitoring / Inspection - Project / Modification - RCA / Improvement time - Admin / Non-maintenance time	All options selected (with 1 exception) – these are all types of work that will take place at Site 5, and it is useful to have a dedicated WO Type for each so that the associated work can be planned, scheduled and recorded. The only exception is "Admin / Non-maintenance time" – this WO Type will not be utilised because in Site 5's context there is no benefit in generating, planning and scheduling a WO every time someone needs to fill out paperwork or go on a training course, for example. If a technician is unavailable for maintenance because they are doing admin tasks, then they will simply be marked as an unavailable resource on the schedule (see step 4.06).	The WO Types listed were made available within Site 5's CMMS.
2.20 [Optional] Review Emergent Work Backlog	Periodically monitor the size and scope of the Emergent Work Backlog (i.e. all Emergent Work that is approved but not yet executed).	Option selected – as discussed in the framework commentary (see section 8.2), this is a critical measure for highly reactive or maintenance intensive assets, which is the expectation for Site 5.	

Framework Step	Options Available	Option selected at Site 5 (with reason)	Phase 1 Reference
2.25 High Priority Emergent Work Strategy	For High Priority Emergent Work: - **[Option A]** Screening, Planning and Scheduling is Fast-tracked - **[Option B]** Bypass Screening, Planning and Scheduling; Proceed directly to Execution	Option A selected – the site's organisation structure is very lean with relatively few labour resources. In this context, it is important that every single task is properly screened and checked before going ahead and consuming these limited resources, which need to be used wisely to address agreed priorities. The site is also expected to be a very maintenance intensive with a large volume of high priority emergent work. In this context, if such tasks are allowed to bypass screening, then due to their significant number this could severely undermine the MD process (i.e. people could be inclined to make exceptions for non-urgent work also). Additionally, because the site is a nuclear site with very strict safety rules, every single Emergent task, no matter how urgent, will already (by law) require several safety processes to be followed prior to execution (e.g. permit to work, risk assessment, written method statement). A WO can easily be created in parallel to these processes without significantly adding to the job preparation time.	

Table 21 – Decisions made during MD process design for Site 5, using Framework v2, section 2.

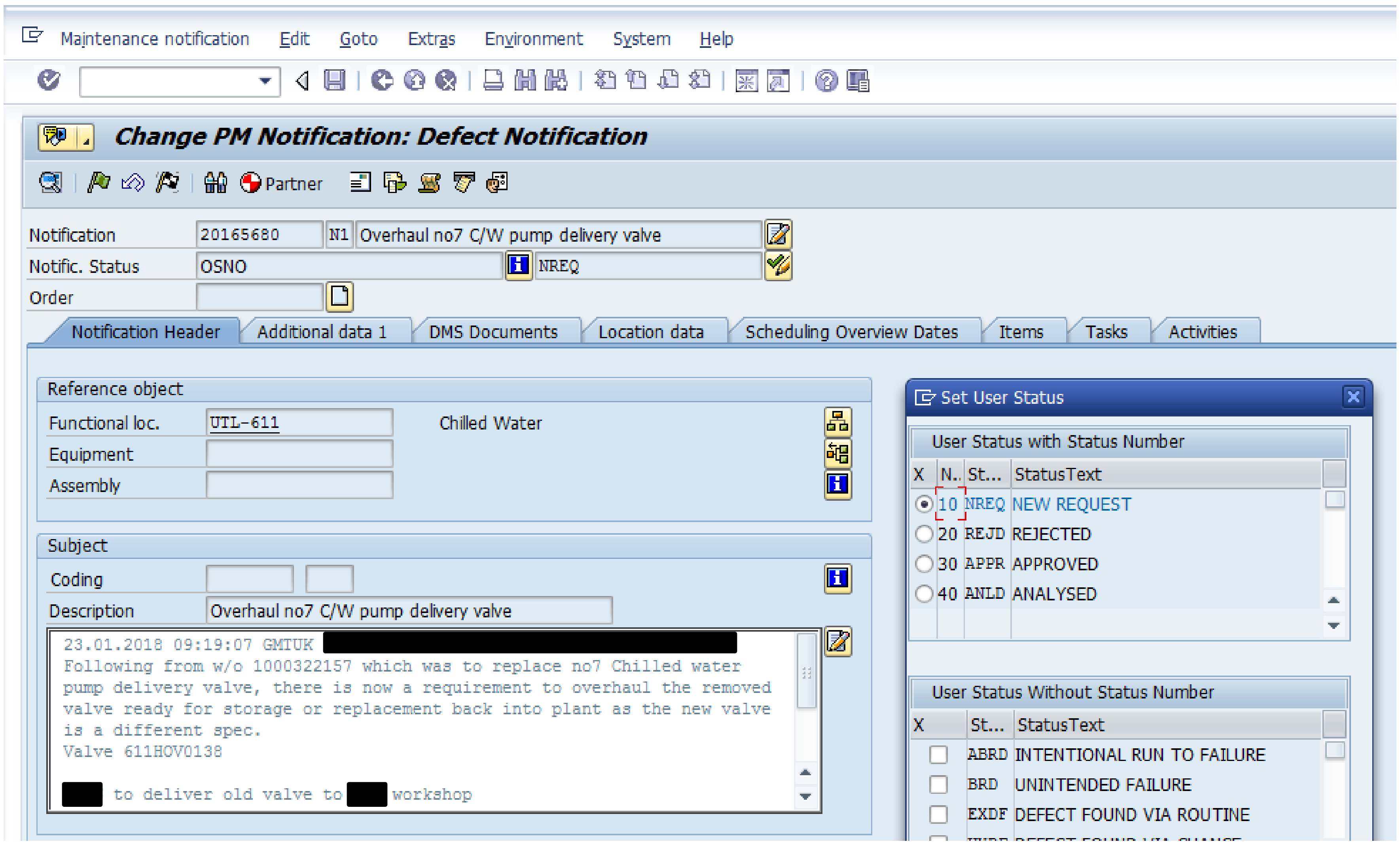


Fig. 13 – Example of a WO Request at Site 5, showing status options

As can be seen in the screenshot above from the Site 5's CMMS (Fig. 13), the WO Request status options align to those selected in framework section 2, steps 2.05, 2.11 and 2.13 (as recorded in Table 21). Note that in SAP terminology, a WO Request is called a "Notification".

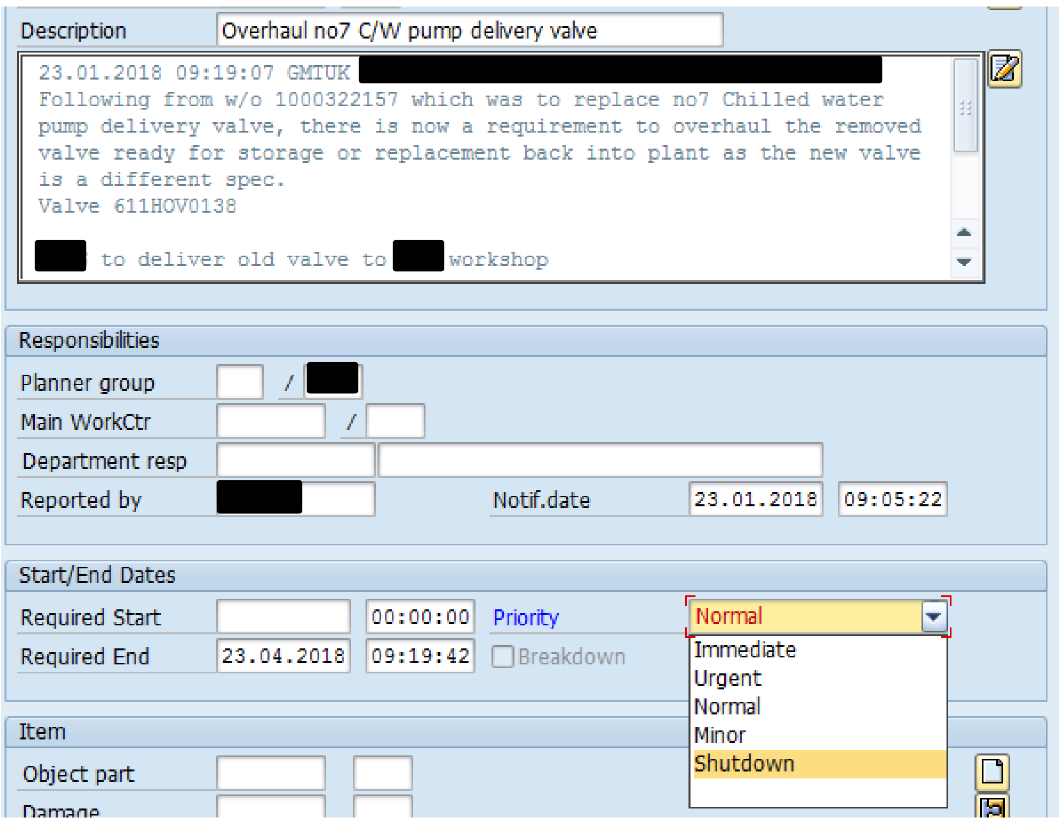

Description
Overhaul no7 C/W pump delivery valve
23.01.2018 09:19:07 GMTUK [redacted]
Following from w/o 1000322157 which was to replace no7 Chilled water pump delivery valve, there is now a requirement to overhaul the removed valve ready for storage or replacement back into plant as the new valve is a different spec.
Valve 611HOV0138
[redacted] to deliver old valve to [redacted] workshop
Responsibilities
Planner group / [redacted]
Main WorkCtr /
Department resp
Reported by [redacted]
Notif.date 23.01.2018 09:05:22
Start/End Dates
Required Start 00:00:00
Required End 23.04.2018 09:19:42
Priority Normal
Breakdown
Immediate
Urgent
Normal
Minor
Shutdown
Item
Object part
Damage

Fig. 14 – Example of a WO Request at Site 5, showing a linear priority scale

The screenshot above (i.e. Fig. 14), taken from the same WO Request as shown in Fig. 13, demonstrates the linear priority scale that has been implemented in the CMMS, as a direct result of selecting option A in framework step 2.14 (as recorded in Table 21). Also visible is the “Shutdown” priority option, which is a direct result of the decision made for step 2.15 of framework section 2 (also as recorded in Table 21).

Terms of Reference

Meeting: **Emergent Work Screening Meeting (Daily)**		
Attendees: **Production Shift Manager, Maint Team Leaders, Maint Planner, Maint Scheduler**		
Optional: **Maintenance Manager**		
Location: **Maintenance Planning Room**		
Duration: **As needed ~ 15 min**	Time: **08:30**	Frequency: **Daily (Mon – Fri)**
Objectives *(What?)*: **1. Feed back on any emergent issues which could impact today’s maintenance schedule** **2. Accept or Reject all new Notifications** **3. Review / Amend today’s Maintenance Schedule as required**	*Why?*: *1. To check if today’s fixed schedule, which was agreed the previous day, is still achievable* *2. So that new requests for emergent work can be progressed (agree Scope, Priority, Owner)* *3. To safely and effectively react to any emergent issues*	
Agenda *(How?)*: o **Review Previous Action Log** o **Feed back on:** o **Plant status changes which could impact today’s maintenance schedule** o **Any ongoing Immediate priority WOs** o **Review status of the previous days scheduled work orders.** o **Review all new SAP Notifications** a. **Review scope definition** b. **Agree Notification is Valid and should be progressed** c. **Message Initiator if Notification rejected** d. **Confirm or amend suggested Priority** e. **Create WO** f. **Assign most appropriate WO owner / planner (amend Planner Group field)** g. **Agree plan for those identified as ‘Immediate’** h. **Ensure Notification Due date is populated.** o **Review today’s current Maintenance Schedule and agree necessary changes in line with emergent priorities:** o **Safely and effectively accommodate any new Immediate priority WOs or plant status changes.** o **Agree new Action Log**		
Inputs: o **Plant Status** o **Previous Action Log** o **Status of Immediate priority WOs** o **New (unprocessed) Notifications** o **Current Maintenance Schedule**	Outputs: o **Work Orders with agreed:-** o **Scope** o **Priority** o **Owner (Planner Group)** o **Informed Initiator if Notification Rejected** o **Awareness of Plant Status** o **Updated Maintenance Schedule** o **Updated Action Log**	

Fig. 15 – Terms of Reference for Daily Emergent Work Screening Meeting at Site 5

The Terms of Reference / Agenda shown above (Fig. 15) for the site’s daily Emergent Work Screening meeting demonstrates numerous steps from framework section 2 that have been implemented. The existence of such a routine meeting with multiple stakeholders from different departments is a direct result of selecting option A in step 2.07, and every item on the agenda relates directly to steps 2.07 – 2.16 from framework section 2.

9.5. *An Assessment of the Impact of the Framework Implementation*

This section aims to demonstrate that the new MD practices implemented in the sponsor company (specifically at Site 5 as described in section 9.4) have successfully closed the MD-related gaps that were identified in the sponsor's AMS, by utilising the same assessment criteria that were originally used to identify them (as documented earlier in section 4 of this report).

9.5.1. Methodology

Recall that the original assessment of the sponsor's AMS, as described in section 4 of this report, had two stages:

1. A documentation-based review – i.e. an assessment of all AMS documentation, in order to determine its completeness against the ISO 55000 requirements.
2. A practices-based review – i.e. an assessment of the observable processes, procedures and systems implemented at the company's sites.

In the Problem Definition (see section 5 of this report), it was explained that all documentation-based gaps that were identified by the assessment would be resolved outside of the scope of this research project. This was because these gaps (i.e. the lack of adequate company policies and procedures that fully met the requirements of the ISO 55000 standard) were considered to be relatively trivial problems that would not require an innovative, research-based solution (although it was work that was carried out by the author nonetheless (Catt, 2015b; 2015c; 2017)). This project instead chose to focus on developing a solution to the gaps identified in the practices-based assessment, because these gaps were more significant, complex, and provided more scope for innovation.

Recall from section 4 that the practices-based assessment utilised the results of an external audit carried out by a third-party consultancy firm (Anonymous, 2014a), utilising an assessment methodology derived from the Institute of Asset Management's self-assessment tool (Institute of Asset Management, 2019). They were employed by the sponsor in 2014 to investigate the company's AM practices following a significant plant failure at the sponsor's UK site (Anonymous, 2013b). The author was fortunate in being able to utilise the results of this assessment to provide an independent, external appraisal of the gaps in the sponsor's AM practices. Ideally, the same external consultants would have been invited back to the company in order to carry out the same assessment at Site 5 in 2018, in order to prove that all gaps had now been resolved by the implementation of the framework. Unfortunately, such a repeat assessment could not be carried out because its cost would have stretched beyond the budget of this EngD project. The only feasible alternative was for the author to carry out the assessment instead by utilising the original methodology, which consisted of a multiple-choice questionnaire (Anonymous, 2014b).

Unfortunately this approach raised two problems, which are discussed below:

1. The first was the lack of an independent assessor – the author clearly had an incentive for this project to succeed, and therefore the questionnaire responses had the potential to include a positive bias. It was recognised that this could be countered by utilising an independent person to carry out the assessment – but since this was a solo EngD project, such resources were not available.
2. The second issue was that, for commercial reasons, the external consultancy did not share their assessment methodology in full. Whilst a copy of the blank questionnaire was made available (Anonymous, 2014b), the method for translating the raw questionnaire responses into final scores for each AM subject was unknown. The final scores for each subject (which were utilised in the original practices-based assessment in section 4) were out of a maximum of 5 points; yet each question in the questionnaire carried a maximum of 4 points (i.e. each question had 4 possible responses with values of 0, 1, 3 or 4 points), and the number of questions in each section was highly variable. It was also not clear which questionnaire sections corresponded to which AM subject (i.e. there were 17 sections in the questionnaire, but there were 24 AM subjects featured in the final scoring system, and their descriptions did not directly correlate). One approach could have been to completely ignore the final scoring system and instead just assess whether the new questionnaire responses at least improved upon the old ones at an individual question level. However, the problem with this approach was that the original questionnaire responses were also not available – only the final scores for each subject (i.e. out of 5) were provided in the final audit report (along with some summary comments) (Anonymous, 2014a).

Problem 1 above was resolved by making the new assessment as transparent as possible: the entire raw data set – i.e. all questionnaire responses – are presented in full in Appendix H so that they are available for further scrutiny if necessary. Clear justification is provided for each and every response, with reference to the appropriate framework step or section that has been implemented at Site 5. Evidence that this implementation genuinely occurred was also documented in detail, examples of which can be found in Figs. 13, 14, and 15 at the end of section 9.4.1.

Problem 2 was resolved by first analysing all questionnaire sections to determine which ones belonged within the scope of MD, so that the assessment could concentrate only on the relevant topics (refer to the conclusions of the literature review in section 5.3 for a full definition of the scope of MD).

This analysis concluded that 5 out of the 17 questionnaire sections were relevant to the scope of the framework, with a combined total of 98 questions (see Appendix H). It was also discovered that even within those sections that were categorised as relevant to MD, there were still a small number of questions that were not completely aligned to the scope of the framework. These questions were still answered, but they were highlighted in red text and analysed afterwards in order to:

- explain why they were not included in the scope of the framework;
- discuss the impact that their absence had on the result of the assessment;
- discuss whether or not additional content should be added to the framework in the future to cover these "red" practices, in order to produce a more complete MD solution.

After the questionnaire was completed, for any responses that did not score the maximum 4 points, further analysis was also carried out to:

- explain why this was the case – e.g. were practices missing from the framework, or was the implementation insufficient?
- investigate whether the original assessment in 2014 would have scored higher (i.e. did the implementation have any negative effects?)
- judge whether the framework required further modification in the future to incorporate additional practices, in order to make a 4 out of 4 score possible.

An example questionnaire section is shown below in Fig. 16 to demonstrate the assessment process (again, questions that focused on framework section 2 were selected for continuity with the rest of this report). Note the number of points awarded in the "points" column, complete with the author's justifications in the "remarks" column. For the full assessment and all questionnaire responses see Appendix H.

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
27								
G	**Planning & Scheduling**		0 point	1 point	3 points	4 points	points	Remarks
G.1	Is there a system of work **requests / notifications and work orders**?		no system in use	no written information, only verbal communication	jobs are listed and communicated verbally	there is a system of written /electronic requests and work orders	4	This is the intent of framework section 2
G.2	What percent of production personnel **generate requests / notifications for work orders** for critical systems		less than 40 %	40 - 64 %	65 - 94 %	95 % or more	4	Framework step 2.04, option A implemented
G.3	Does the work request contain **all necessary information**?		no requests	only short description of work to be done	request mentions nearly all needed information	For critical systems all work requests are related to equipment numbers. Prioritization is ranked.	4	Framework step 2.04 implemented with appropriate mandatory fields
G.4	When **will work orders be created** for critical systems in CMMS?	x	not at all / after execution	most time after execution	only for planned jobs before execution	before execution of all kind of jobs including emergency breakdown.	4	Framework step 2.25, option A implemented
G.5	Is there a description / procedure how work order requests are systematically evaluated/selected to be executed or not (**work order selection - "gate keeping"**)?	x	no procedure	procedure exists, but not followed , everybody on production side can decide	definition of responsible persons, but not fully implemented procedure	lived procedure with definiton of responsible person(s)	4	This is the primary intent of framework section 2
G.6	Is there a description / procedure how work orders are systematically **prioritized?** (e.g. RBWS - Risk Base Work Selection)	x	it is random and based on emergency needs	is set by maintenance with minimal operations input	weekly in a joint production / maintenance meeting	daily in a joint production / maintenance meeting	4	Framework step 2.14, option A implemented
G.7	Is there a person on production / operations side who decides at which **"latest date"** the work order shall be finished for critical systems?	x	no procedure	procedure exists, but not followed , everybody on production side can decide	lived procedure with definiton of responsible person(s)	lived procedure, latest date for finishing preventive W.O. is pre-defined	4	As above. Latest dates are linked to priority selection
G.8	Testing of **critical equipment**. Is it scheduled automatically and reported back.	x	No scheduling for testing	Testing is scheduling in different system	All critical equipment is scheduled for testing, no reporting	All critical equipment is scheduled for testing and result is reported	4	Testing requirements come from step 1.24; result is reported at framework step 5.29
G.9	Is a **maintenance / service category** (like preventive maintenance, inspection, repair, modification, etc.) defined for each job for critical systems?		less than 64 %	65 - 94 %	95 % and more	All	4	100% - mandatory field. Optional framework step 2.18 implemented
G.10	What percent of work orders processed in the system are tied to an **equipment / asset number** (TAG-number) for critical systems?		less than 64 %	65 - 94 %	95 % and more	All	4	100% - mandatory field. Framework step 2.04 implemented
G.11	What percent of work orders are opened under a **priority** that would be identified as **emergency or high priority (prio 1)**?		more than 40 %	26 - 40 %	15 - 25 %	less than 15 %	4	8.6% as of 08/02/2018.
G.12	Is a satisfying part of **workload planned**? (Quality of planning & scheduling)		Firefighting, daily meetings, maintenance agrees with production on activities each day, < 30 % of maintenance workload is planned	Weekly schedule established, but followed < 50%	Weekly schedule established and followed between 50% and 80%	Weekly update of bi-weekly schedule with detailed plans, > 80% on weekly schedule.	4	100% of work is planned and scheduled: Framework step 2.25, option A implemented Framework step 3.01, option A implemented Framework step 4.04, option A implemented

Fig. 16 – Example questionnaire responses, section G "Planning & Scheduling", related to Framework section 2

9.5.2. Results Summary

After analysing the questionnaire responses, the maximum number of points was achieved for almost every question: only 4 out of 98 questions did not score the maximum 4 points – and in all of these cases, the original score in 2014 was determined to be the same or lower anyway. Furthermore, in 2 of these cases, the non-maximum score was due to the outdated rating criteria of the questionnaire, rather than due to poor practices being identified at Site 5.

As discussed in section 9.5.1, the connection between the 17 questionnaire sections and the 24 AM subjects featured in the audit's final scoring system was unknown. However, it could be safely assumed that the subjects listed below in Table 22 (along with their 2014 scores) correlated well with the scope of the framework:

AM Subject	Score awarded in 2014 audit
Work Processing	2.1 out of 5
Information Management	2.0 out of 5
Performance and condition monitoring	1.8 out of 5
Investigation of failures	2.4 out of 5
Improvement Actions	2.1 out of 5
Spare Parts Management	2.2 out of 5
Outsourcing	3.6 out of 5

Table 22 – Final scores for all relevant AM subjects featured in the 2014 external audit (Anonymous, 2014a)

It was clear that from the extremely positive questionnaire responses for Site 5 in 2018 (i.e. with only 4 out of 98 questions NOT obtaining the maximum 4 points), that the final scores for the assessment sections listed above would have been in the very high 4's in all areas, which was considered to be a significant improvement.

9.6. *Conclusion*

Based on the results summary shown above in section 9.5.2, the implementation of the framework at Site 5 had clearly delivered a significant improvement in MD practices, when compared to the existing practices that were in place at the Sponsor Company in 2014 before this project started. This result successfully demonstrated that this project had closed the gaps originally identified in the Problem Definition.

As further evidence, in Jan 2018 the sponsor's new IT director commissioned an internal audit of each site's CMMS and MD systems for benchmarking purposes, utilising a third party AM consultancy firm (a different company to the one used in 2014) (Anonymous, 2018a). Whilst this audit was less structured than the 2014 audit (i.e. there was no formal question set, it was more of an open discussion and demonstration to the panel of consultants), it did provide an independent assessment of the MD practices at each of the sponsor's sites, after the implementation of the framework at Site 5. The conclusion was that Site 5 was overwhelmingly the best practice site in the business, as this email from the lead consultant to the sponsor's IT Director demonstrates:

> *"I visited last week [Site 5] / Phil Cat and his team and I was positive surprised by the setup of the SAP EAM/Plant Maintenance system for the [Site 5] Installed Base. I advise you to contact Phil and that you exchange with them lessons learnt but also the knowledge which they build up in their team. [The sponsor company] has here the chance to move to a more harmonized system and also doing things more efficiently.* ***I really consider the [Site 5] setup as the best-practice within [the sponsor company]*** *and of course we can extend functionality as demonstrated in my slides"* (Anonymous, 2018b)

As a result of this audit, Site 5 was recognised as the best practice site in the sponsor company, and the author was appointed as the leading expert in all matters relating to MD process design and CMMS functionality in the business.

9.6.1. Innovations

The successful implementation of the framework in the Sponsor Company demonstrated the two principal innovation claims of this research: claim 1 being that the framework can deliver a tailored business process to suit any context, and claim 2 being that the framework can deliver a tailored CMMS implementation specification that fully supports that business process.

During implementation phase 1, the framework was successfully utilised to develop a series of CMMS implementation specifications for each of the sponsor's sites, which validates claim 2 (see section 9.3). These specifications were later used to successfully procure, implement and configure additional CMMS functionality in support of the business process design; a total of 57 CMMS improvements were implemented by this method (i.e. the 60 identified in section 9.3, minus the 3 that were de-scoped in section 9.3.1 due to cost limitations). The fact that each site was able to select different tailoring options (see the example in Table 15) proves that the solution developed by this research (i.e. the framework) fully answers the research question (i.e. the solution is *detailed* yet *flexible* – see section 5.1.5).

During implementation phase 2, the framework was successfully utilised to develop a tailored business process for Site 5, which validates claim 1. The development of this process (as described in section 9.4) also demonstrates the inherent flexibility of the framework, because so many of the detailed tailoring decisions were able to take into account the specific context of Site 5 (i.e. a maintenance-intensive, highly regulated nuclear site with a relatively small workforce). The resultant process was highly detailed and perfectly tailored to suit Site 5's requirements – and it was ultimately successful in closing the gaps identified in the Problem Definition, as demonstrated by the positive assessment results in section 9.5.2.

9.6.2. Limitations

Whilst this project has clearly demonstrated the framework implementation process, and proven that all gaps from the original Problem Definition have been closed, it has not demonstrated that by closing these gaps, AM performance has actually improved at the sponsor company. The main reason for this is that Site 5, as a new plant, has no previous performance data with which to draw a comparison (it was already explained earlier in section 9.4 that the implementation was carried out at Site 5 rather than at the more established sites due to there being fewer barriers to introducing significant change in a short period of time).

One could counter this argument by asking why Site 5's performance in 2018 could not be compared to historical performance data from the sponsor's other sites. Firstly, the other sites operate in a very different context (i.e. different assets, different ages, different processes, different products etc.) and therefore many performance measures would simply not be comparable. However, there are a small number of maintenance performance measures that are arguably universal and could be compared between assets in different contexts (e.g. on-time completion of work; reactive / preventive maintenance ratio; defect backlog; resource utilisation, etc.). However, as described in the original assessment of the sponsor's AMS (see section 4), there is no historical performance data for the sponsor's other sites – prior to the new MD process implemented at Site 5, maintenance performance was never measured at the sponsor company (that was after all one of the original gaps that the framework was designed to resolve).

Nonetheless, attempts were made by the author to extract historical WO data from the sponsor's CMMS, in order to manually construct retrospective performance measures for the other sites, for the purposes of comparison with Site 5 in 2018. To produce the fairest possible comparison, data from the sponsor's USA site was selected because, as the newest plant in the business (which began operations in 2010), WO data was available from the site's commissioning and early operational phases, making it comparable with Site 5's current context. Additionally, data was only selected for the plant utility systems (e.g. compressed air, electrical distribution, process water) because these types of assets are common to both sites.

However, the findings were disappointing. WO data was found to be largely incomplete or missing at the USA site, to the extent that reliable performance measurement was not possible. Historical maintenance records were largely missing: for example there were only 2 Work Orders in the USA CMMS for the entirety of 2010. This was despite the presence of 45 WO Requests, which demonstrated that the plant was clearly operational (all requests were in core process areas that would have been commissioned last). Routine maintenance was clearly being recorded outside of the CMMS in the early life of the USA plant, making the data inaccessible for measurement purposes.

Even when looking at the latest WO data from the sponsor's other sites, actual finish dates and actual hours spent on tasks were not recorded for the majority of WOs. Significant numbers of assets were not registered in the CMMS, which was evidenced by defects being raised against system-level locations. Evidence was also found of WOs being arbitrarily and incorrectly categorised (e.g. as predictive when they were actually reactive, based on the accompanying text). These findings meant that performance could not be measured at the sponsor's other sites in any reliable capacity at any point in their history.

These findings explain why, unfortunately, an improvement in AM performance could not be demonstrated after the introduction of the framework. Prior to this project, it was not possible to measure maintenance performance at the Sponsor Company. However, one could argue that this is a substantial improvement in itself – i.e. due to the improved MD practices introduced as part of this project, data quality is now good enough to enable reliable performance measurement, and the CMMS is capable of generating KPI reports for routine analysis and improvement.

One other limitation was recognised – not with the methodology of the assessment– but with the framework itself. Whilst the framework is very useful in assisting with the design of an MD process, it doesn't explain how to successfully implement one. Many of the "red" questions in the questionnaire demonstrated this (i.e. those questions not completely aligned to the scope of the framework, see section 9.5.1). For example, issues related to user training, support, "user-friendliness" of the CMMS interface, and techniques for overcoming people issues such as culture and attitude etc. – these issues are simply not covered in the framework, and they are arguably quite important. These omissions should be resolved as further work in the future (see next section).

9.6.3. Further work

Due to the limited time available for this project, it was not possible to implement every aspect of the framework in full. There were several practices that were highly desirable for Site 5, but there was simply not enough time or resources to implement them during this project. However, the author will continue working on the implementation of these items in the near future as part of his job role at the Sponsor Company. The more significant items that will be addressed next include:

- The ability to carry out Maintenance Requirements Analysis within the CMMS (i.e. Framework step 1.14).
- Enhanced physical labelling of assets with barcodes and criticality ratings (i.e. Framework step 1.22).
- The ability to raise and process Due Date deferral requests via the CMMS (i.e. Framework steps 4.07 and 4.08).
- The ability to record a Reason Code when a schedule break occurs and a WO needs to return to the planning stage (i.e. Framework step 5.20).

- The ability to execute several MD process steps via a mobile device, i.e. the creation of WO Requests (i.e. Framework step 2.04), confirmation of completed work (i.e. Framework step 5.29), and booking the actual time taken to complete a task (i.e. Framework step 5.30).

On the last point regarding mobile devices: it was stated earlier in section 9.4.1 that the benefits of utilising mobile devices in a centralised plant such as Site 5 were not as significant as in those companies with a large, geographically extensive asset base. However, this option is currently being considered due to the improvements mobile apps can bring to the user interface of SAP (which has room for improvement as discussed earlier in sections 9.3.2 and 9.6.2).

Additionally, there were several questions from the assessment (i.e. section 9.5) that identified additional practices that could be included in the framework in order to improve it further – these will also be actioned by the author after the end of this project:

- The practice of recording working hours spent on each work order at least daily in order to keep such information current.
- The practice of recording technical completion of WOs should take place at least weekly in order to keep such information current.
- The practice of recording commercial completion of WOs should take place at least monthly in order to keep such information current.
- Other aspects of Materials Management – such as inventory management, stock control, demand forecasting, and procurement – that were deliberately excluded from the MD framework in section 5.3.7, should be added to the framework in a future version.
- Include the distribution of KPI reports to relevant stakeholders (i.e. notice boards, flat screens, engineers, planners, supervisors, management team).
- Investigate how to successfully implement a new MD process in an existing organisation that is resistant to change, and incorporate these findings into the framework.
- Include a full management of change (to assets) process within the framework.
- Include a budgeting / resource management process within the framework.

- Specify that operations and maintenance technician involvement in improvement work is beneficial because it improves their engagement in the improvement process, which will in turn result in more improvement suggestions.

10. Innovation Summary

This section will summarise the innovation delivered by this project. Emphasis will be placed on why each claim is considered to be novel, non-trivial and beneficial, in accordance with the innovation definition that was established earlier in section 6.3.2 (Berkun, 2013).

10.1. *Innovations related to the Research Aim and Objectives*

The innovations described in this section relate directly to the principal aim and objectives of this research. Recall the Research Aim Statement that was formally defined in section 5.1.5:

> ***This project will deliver a comprehensive framework of MD practices containing multiple options from many different industries and sectors, from which the end user can make informed selections in order to develop a detailed business process that is tailored to suit their specific context.***

Therefore this section will present and discuss all innovations related to the tailorable framework of practices for MD (which is presented in full in Appendix D). The discussion will be structured in line with the Research Objectives that were formally defined in section 5.1.6. Table 23 below provides a summary of each of the 5 ROs and maps them against the associated innovation claims / knowledge contributions and their impact. Each innovation claim is then discussed in further detail in the following sections of this chapter.

Research Objective	Related Innovation Claim(s)	Impact / Value
1. Review the literature to clearly define the scope and boundaries of the framework	The framework scope (see section 10.1.3).	The scope of the framework, defined in response to RO 1, covers multiple AM subject areas that are not usually included within the scope of MD. This widening of the MD subject area beyond its usual limits results in a more effective and holistic solution for the end user.
2. Analyse the literature from within these defined boundaries to extract all MD practices and develop a preliminary version of the framework	New knowledge discovered in industry that was not present in the literature (see section 10.1.4). New practices that were neither present in the literature nor industry (see section 10.1.5).	During the development of Framework v1 (i.e. in response to RO 2), 24 practices were added by the author (based on ideas and experience) that were not present in the literature, despite an extensive search. When investigating these in industry (i.e. in response to RO 3), 21 of the practices were verified by experts as genuine industry practice, enabling this research to add to the body of knowledge. Furthermore, three practices were found to be completely novel according to all 12 participants, meaning that they improve upon the content found in the literature and go beyond the practices found in industry. They were found to be beneficial in contexts with mature CMMS practices, including the sponsor company.
3. Develop the literature-based framework further by utilising expert opinion from industry		
4. Apply the framework in the Sponsor Company; use it to develop and implement an improved MD process	The tailorable nature of the framework (see section 10.1.1). The CMMS implementation specification (see section 10.1.2).	The fact that the framework is fully tailorable and able to produce an effective MD process for any context is the main innovation claim of this project (i.e. the response to the Research Aim Statement). In addition, the framework is also able to deliver a fully aligned CMMS implementation specification that is also tailored to the same contextual requirements, ensuring that the end user can purchase, implement and configure a CMMS that has the necessary capabilities to fully support their tailored MD process. These innovations were successfully demonstrated by the application of the framework in the sponsor company (i.e. in response to RO 4) and the subsequent evaluation (i.e. in response to RO 5), which demonstrated significant improvement in the MD practices at the site, to the extent where all gaps from the problem definition had been closed.
5. Evaluate the effectiveness of this implementation and demonstrate that it closes the MD-related gaps found in the Sponsor's AMS		

Table 23 – Summary of innovation claims mapped against the Research Objectives

10.1.1. The tailorable nature of the framework

The main premise of the framework and its central innovation claim is that it facilitates the development of a fully *tailored* business process for MD. This innovation was necessary in order to answer the Research Question that was defined in section 5.1.5, i.e.:

> ***How can a process be developed for Maintenance Delivery that is detailed and robust enough to ensure good practice, yet is still flexible enough to be effective in any context?***

The framework contains options from multiple different industries and sectors (sourced from both the literature and from industry), enabling the end user to consider practices from a wide range of sources, in order to develop a detailed and effective MD process to suit any context. A generic, universal framework that is flexible enough to be useful in many different industries is novel, because existing MD processes are generally designed for a single, specific case and cannot adapt to different contexts (as proven by an exhaustive review of the literature in section 6). The size and scope of the framework validates the claim that it is non-trivial – i.e. a series of flowcharts covering multiple AM subject areas, with 157 core process steps, 109 contextual options, and 30,000+ words of guidance (see Appendix D).

The framework is also undoubtedly beneficial, as demonstrated via its successful implementation in a real industrial case, that delivered significant improvements to MD practices (see section 9 of this report). The framework was successfully utilised to develop and implement a highly effective MD process that was perfectly tailored to suit a very specific context (i.e. a maintenance-intensive, highly regulated nuclear site with a relatively small workforce). This successful implementation demonstrated the inherent flexibility of the framework, thus fully answering the research question.

The framework has the potential for application in a wide variety of industries beyond the sponsor of this research, i.e. in any business that plans and controls maintenance activities. This claim was validated by feedback from industry professionals who reviewed the framework during the Delphi study that was described in section 7:

- "A formal business process for MD – agreed, documented, signed off, and aligned to the functionality of the CMMS – is very valuable; such a tool is not available in my organisation. This causes several problems: a lack of consistent strategy, and poor data quality which prevents analysis and improvement in performance." (Participant 10).

- "The MD process certainly needs to vary to suit the manufacturing process if it is going to be effective. Different industries will have different requirements, and your framework rightly allows for this." (Participant 12).

10.1.2. The CMMS implementation specification

As well as a tailored MD process, the framework also generates a fully aligned implementation specification for the supporting CMMS, which is also tailored according to the same contextual requirements. This enables the end user of the framework to not only create a tailored MD process, but it also ensures that they are able to purchase, implement and configure a CMMS that has the necessary capabilities to fully support that process. This feature is innovative because it combines a tailored business process design tool with a software specification tool (in a novel way) to solve a significant industry problem (i.e. frequently sub-standard CMMS implementations with insufficient functionality, as discussed in section 5.3.1).

The benefits of this feature were demonstrated in section 9, whereby the framework was successfully utilised to develop a series of CMMS implementation specifications for each of the sponsor's sites. These specifications were later used to successfully procure, implement and configure additional CMMS functionality in support of the business process design; a total of 57 CMMS improvements were implemented by this method. The fact that each site was able to select different tailoring options to suit their local context (see the example in Table 15) also proves that the solution developed by this research (i.e. the framework) fully answers the research question (i.e. the solution is *detailed* yet *flexible*).

This feature of the framework further increases its potential for application in industry, because it offers a clear solution to a common industry problem (i.e. poor CMMS implementation, as discussed above). This claim was validated by feedback from industry professionals who reviewed the framework during the Delphi study that was described in section 7:

- "In reality, most CMMS implementations are badly done. An implementation specification such as the one you are proposing would be a useful guide to prevent this." (Participant 7).

10.1.3. The framework scope

Another aspect of the framework that makes it novel is that it covers multiple AM subject areas that are not normally combined via a single, holistic solution. Looking back to the definition of Maintenance Delivery that was sourced from the Global Forum on Maintenance and Asset Management (2014) (see section 5.1.3), a MD process typically involves managing the execution of maintenance activities, including both preventive and corrective tasks, whilst also considering the infrastructure of the supporting CMMS. However, the framework is novel in that it takes the subject of MD beyond these existing boundaries by incorporating numerous other AM processes into the solution, i.e.: performance measurement, continuous improvement, root cause analysis, maintenance requirements analysis, parts acquisition, and the execution of STO activities. This widening of the framework scope also has significant benefits for the end user, as their resultant MD process will be more holistic and better integrated with several closely related AM subjects, which makes for a more effective overall solution.

Again, this claim was partly validated by feedback from industry professionals who reviewed the framework during the Delphi study that was described in section 7 (i.e. with respect to the inclusion of framework section 6 that focuses on performance measurement, root cause analysis (RCA), and continuous improvement):

- "Including a section on improvement is a good addition that is often left out of MD systems – this is a major component of ISO 55000 and needs to be integrated into the MD process if it is to work" (Participants 8, 12).

This section of the framework is especially innovative in that it recognises that performance measurement and RCA are routes to the same outcome (i.e. improvement), and subsequently combines them via a holistic and consistent improvement process. And this process is in turn fully integrated into the wider MD process – utilising the same WO-based control mechanisms and the same pool of resources – ensuring that improvement activities are conducted alongside maintenance activities as a part of the normal day-to-day workflow.

10.1.4. New knowledge discovered in industry that was not found in the literature

During the development of the framework, 21 practices were added directly by the author because, whilst they were known to be practiced in industry, references could not be found in the literature despite an exhaustive search (see section 6). These practices were later verified by industry experts as genuine industry practice, enabling this research to add to the body of knowledge (see section 7). Although the execution of these practices in industry is not novel, their inclusion in a published framework or model is novel – a fact that adds to the innovative nature of the framework.

10.1.5. New practices that were neither present in the literature nor industry

The framework also contains 3 new practices, based on ideas that were conceived by the author during the development of the framework, that improve upon the content found in the literature and go beyond the practices found in industry. They are all items of additional CMMS functionality that can be realised through creative software configuration – see section 7.5.1 of this report for more details (i.e. Table 10). Whilst these practices were proven to be novel, they were found to be beneficial only in a limited number of contexts (i.e. typically contexts that had very mature CMMS processes – those with basic systems did not appreciate the benefit). For this reason, they will be considered as minor additional innovations that supplement the main innovation claim of this project (which is of course the framework itself). Note that when implemented in the sponsor company, these 3 new practices were certainly beneficial and can therefore be considered innovative in the sponsor's context.

10.2. *Other Innovations*

This section will discuss several additional innovations that are not directly related to the main deliverable of this research (i.e. the framework). The author plans to publish a paper at a later date focusing on their development and application because, although they are not directly related to the Research Question, they are nonetheless interesting solutions to ancillary problems that were encountered along the way.

10.2.1. The "Codebook"

The "codebook" developed in section 3.2 of this report (see Appendix A) is an innovative assessment tool for determining if an AMS meets the requirements of ISO 55001 (or the requirements of several other prominent AMS requirements frameworks, such as PAS 55, if desired). It presents the requirements of the ISO standard in a concise manner with a very clear structure, enabling the end user to assess their AMS much more easily than they could if utilising the source document (which is poorly structured with a great deal of repetition and internal cross referencing). The codebook can be considered novel because an exhaustive literature review of AMS requirements frameworks was carried out during its development, and nothing comparable was found – all existing frameworks were presented in a prose format, making their requirements rather ambiguous, subjective and open to interpretation (i.e. coding was required in order to unanimously define and understand them). The benefits of the codebook include its potential for application in academia or industry, to assist anyone who needs a definitive list of AMS requirements – either to carry out an assessment of an existing AMS, or to assist with the development of a new one. Both of these uses have been demonstrated during the course of this research: i.e. the sponsor's pre-existing AMS was assessed in section 4, and a new AMS was later developed for the sponsor by utilising the codebook to ensure that all ISO 55000 requirements were incorporated in full (Catt 2015a; 2015b; 2017).

10.2.2. The "AMS components diagram"

The "AMS components diagram" developed in section 5.1.1 of this report (see Fig. 7) illustrates the relationships and inter-dependencies between the 23 AMS components that were defined in the "codebook" (discussed above). It can be considered as a diagrammatical accompaniment to the codebook, which was already claimed previously as an innovative AMS assessment / development tool. It provides a clear and concise overview of all elements of the AMS with specific emphasis on how these elements interact, and if used alongside the codebook it can further facilitate the assessment or development of an ISO-aligned AMS. Although the life-cycle stages included in the diagram have been limited to the asset utilisation phase only in order to align with the scope of this research (as discussed earlier in section 4.1.3), it could easily be expanded to cover other life cycle stages without too much alteration.

The diagram can be considered novel because, although similar AMS diagrams were found in the literature (such as the one found in the ISO 55000 standard (British Standards Institute, 2014a)), they were not as detailed and did not cover all of the 23 AMS components that are specified in the codebook. The fact that the diagram also explicitly incorporates the PDCA (Plan, Do, Check, Act) cycle for continuous improvement also makes it unique, and provides additional benefits for organisations who wish to promote a continuous improvement culture (in alignment with clause 10 of the ISO standard (British Standards Institute, 2014b)).

Another benefit of the diagram is its potential application as a training aid – it is ideal for raising awareness of the AMS and explaining the core concepts of AM in a simple, 1-page format (which is something that organisations need to do in order to comply with clause 7.3 of ISO 55001 (British Standards Institute, 2014b)). The author has successfully used it in this manner to great effect within the sponsor organisation (Catt, 2015b; 2015c; 2017).

10.2.3. The Coding Methodology that was utilised to develop the codebook

Another innovation delivered during this research is the methodology developed in chapter 3.1 – i.e. the hierarchical descriptive coding of a standard in order to interpret, simplify and clearly present its requirements in a structured and concise list. This method, that was utilised in this project to assess and compare AMS Requirements Frameworks, could also be utilised for any other requirements framework (for example other ISO standards) outside of the AM subject area, and could therefore have value in other disciplines such as Quality Management, Health and Safety Management, and Risk Management etc.

11. References

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Appendix A – Codebook showing all AMS requirements against all AMS Requirements Frameworks available in the literature

Section	Section Description	AMS Core Components (letter) & their Requirements (number)		ISO 55001 (British Standards Institute, 2014b)	PAS 55-1 (British Standards Institute, 2008a)	(Department of Local Government, 2011)	(El-Akruti and Dwight, 2013)	(Water Environment Research Foundation, 2005)	(Asset Management Council, 2014)	(US Department of Transportation, 2007)	(Washington State Department of Health, 2009)	(OECD, 2001)	(Crist, et al., 2013)	(Younis and Knight, 2012)	(Brown et al., 2012)
CON	**Organisational Context**	**A**	**Determine the organisational context and how this should impact AM decisions**	x	x			x	x			x	x		x
		A1	Consider the internal context	x		x	x	x	x			x		x	
		A2	Consider the external context	x			x	x							x
		A3	Identify and consider relevant stakeholder's needs and expectations	x	x	x		x	x	x	x	x	x	x	x
		B	**Determine the scope of the AMS**	x	x	x			x						
		B1	The scope must align with the AM policy (Component D) and strategy (Section STRAT)	x											
		B2	The scope must align with the organisational context (Component A)	x					x						
		B3	The scope must align with other company Management Systems	x					x						
		B4	The scope must define the asset portfolio covered by the AMS	x				x	x	x	x		x		x
LEAD	**Leadership**	**C**	**Leaders must show commitment to the AMS**	x	x	x			x						x
		C1	Ensure all AMS requirements are implemented in full	x	x	x									
		C2	Ensure sufficient resources are available to fulfil the requirements of the AMS	x	x	x									
		C3	Ensure there is sufficient cross-functional collaboration to enable effective AM	x											x
		C4	Ensure the required AM performance is achieved and continually improved	x	x										
		C5	Ensure others are sufficiently directed, supported and authorised to be able to contribute effectively to AM performance	x	x	x			x						
		C6	Ensure AMS processes align with and are compatible with other organisational processes	x	x		x								
		C7	Appoint a member of top management who shall have overall responsibility for the development of the AMS		x	x									
		C8	If a change of culture is required to achieve AM performance, ensure that this is led from the top of the organisation	x	x			x		x					x
		D	**Define an AM Policy**	x	x	x	x		x	x		x	x		x
		D1	AM Policy must align to the wider organisational purpose, vision and strategy	x	x					x			x		x
		D2	AM Policy must be consistent with other relevant organisational policies and processes	x	x										x
		D3	Policy must include a commitment to the delivery and continual improvement of AM performance	x	x										
		E	**Define AM Roles & Responsibilities**	x	x	x			x				x		
		E1	Ensure that all roles necessary to deliver the AMS requirements are assigned	x	x										x
STRAT	**AM Strategy**	**F**	**Develop a Risk Management process for AM**	x	x			x	x	x					x
		F1	Align AM risk management with the wider organisational risk management process	x	x				x	x					
		F2	Identify any risks or opportunities that could have an impact on AM performance	x	x					x			x		x
		F3	Consider the organisational context (Component A) when identifying AM risks	x	x				x	x					
		F4	Ensure that these risks are managed as part of the AM Strategy, i.e. risks are fed into the AM objective setting process (Component G) and subsequently plans are put in place to address them (Component H)	x	x				x	x					
		F5	Ensure that emergency situations and contingency planning are considered	x											

Section	Section Description	AMS Core Components (letter) & their Requirements (number)			ISO 55001 (British Standards Institute, 2014b)	PAS 55-1 (British Standards Institute, 2008a)	(Department of Local Government, 2011)	(El-Akruti and Dwight, 2013)	(Water Environment Research Foundation, 2005)	(Asset Management Council, 2014)	(US Department of Transportation, 2007)	(Washington State Department of Health, 2009)	(OECD, 2001)	(Crist, et al., 2013)	(Younis and Knight, 2012)	(Brown et al., 2012)
		FX	**Develop a Contingency Planning Process**			**x**										
			FX1	Identify any asset related risks which could result in an emergency situation, or any emergency situations which could impact critical AM activities		x										
			FX2	Develop plans for responding to these situations to mitigate the likely consequences		x										
			FX3	Ensure those who are required to respond to emergency situations are sufficiently competent		x										
			FX4	Consider the needs of all stakeholders who may be affected by emergency situations		x										
			FX5	Periodically review and test emergency response plans		x										
		G	**Develop a process for setting AM objectives**		**x**	**x**	**x**	**x**	**x**	**x**	**x**		**x**	**x**	**x**	**x**
			G1	The objective setting process must consider the organisational context and the AM decision making criteria (Component A)	x	x	x		x	x	x		x	x	x	x
			G2	AM objectives must align with the wider organisational objectives	x	x				x				x		x
			G3	AM objectives must take input from the AM policy	x	x										x
			G4	AM objectives must be measurable	x	x										x
			G5	AM objectives must be reviewed and updated as appropriate	x	x							x			
		H	**Develop plans to ensure that AM objectives are achieved**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
			H1	Integrate AM objective planning into the wider organisational objective planning process	x	x	x	x								x
			H2	Define appropriate method(s) for determining the content and format of AM plans based on the nature of the objective or asset	x	x	x									
			H3	These methods should include the assessment and mitigation of any risks associated with managing the asset	x	x	x		x	x	x	x	x	x		
			H4	These methods should establish processes and activities to proactively identify potential failures in asset performance and evaluate the need for preventive action	x	x			x		x	x	x	x		
			H5	Plans must detail what will be done, the resources required, the costs associated, when the work will be completed and who is responsible for delivery	x	x	x	x	x	x	x	x			x	
			H6	Define review periods for AM plans	x	x								x		
SUPP	**Support**	**I**	**Develop a process for Resource Management**		**x**				**x**		**x**	**x**	**x**		**x**	
			I1	Determine the resources needed to meet the requirements of the AMS in full	x				x		x	x		x	x	
			I2	Ensure that sufficient provision is made to provide the required resources	x	x									x	
		J	**Develop a Competency Management Process**		**x**	**x**				**x**						**x**
			J1	Determine the competency requirements of all persons that could have an impact on AM performance	x	x	x			x						x
			J2	Take action to ensure that these competency requirements are met through suitable training and experience	x	x			x	x						
			J3	Retain appropriate records as evidence of competency	x	x										
			J4	Periodically review competency requirements	x											
		K	**Raise Awareness of the AMS**		**x**	**x**	**x**			**x**	**x**					
			K1	Ensure that all persons doing work that have the potential to impact AM performance are aware of the AM policy	x	x										
			K2	Ensure that these persons also understand how their work contributes to AM performance, and the potential negative impact if the approved AMS processes are not followed.	x	x				x						x

Section	Section Description	AMS Core Components (letter) & their Requirements (number)			ISO 55001 (British Standards Institute, 2014b)	PAS 55-1 (British Standards Institute, 2008a)	(Department of Local Government, 2011)	(El-Akruti and Dwight, 2013)	(Water Environment Research Foundation, 2005)	(Asset Management Council, 2014)	(US Department of Transportation, 2007)	(Washington State Department of Health, 2009)	(OECD, 2001)	(Crist, et al., 2013)	(Younis and Knight, 2012)	(Brown et al., 2012)
		L	**Determine the requirements for AM Communication**		**x**	**x**	**x**				**x**					
			L1	Determine the requirements for internal and external communication relating to AM, specifying: what will be communicated, how, when and to whom. Specific communication requirements include but are not limited to (L2 - L5):	x	x					x					
			L2	There should be regular communication from leaders on the importance of effective AM and of fully complying with the AMS processes	x	x				x						
			L3	The AM policy should be communicated within the organisation and to other stakeholders as appropriate	x	x										
			L4	The AM objectives should be communicated within the organisation and to other stakeholders as appropriate	x	x					x				x	
			L5	The AM roles and responsibilities required to deliver the AMS requirements	x	x										
		M	**Develop a process for managing AM Information**		**x**	**x**	**x**	**x**	**x**	**x**			**x**	**x**	**x**	**x**
			M1	Determine the information requirements necessary to effectively support all AMS processes	x	x				x						x
			M2	Ensure processes are in place to manage this information appropriately (i.e. collection, storage, analysis, evaluation, obsolescence, archiving)	x	x	x	x		x			x		x	x
			M3	Ensure that there is consistency between different types of AM data, for example financial and technical data	x	x	x									
		N	**Determine AM Documentation Requirements**		**x**	**x**										
			N1	The AMS shall include all documentation necessary to enable the AMS processes to function. Specific requirements include but are not limited to (N2 - N5):	x	x										
			N2	The AMS shall include an "AMS Scope" document which describes the outcome of Component B (AMS Scope)	x	x				x						
			N3	The AMS shall include an "AM Strategy" document which describes Components F (AM Risk Management process), G (AM Objective setting process) and H (process for developing AM Plans) and the details the outcome of process G (the AM objectives)	x	x	x									
			N4	The AMS shall include an "AM Policy" document which describes the outcome of Component D (AM Policy)	x	x										
			N5	An overview of the main components of the AMS and how they interact		x										
		O	**Develop a process for managing AM Documentation**		**x**	**x**										
			O1	Ensure all documentation required by the AMS is adequately controlled, i.e. storage, security, distribution, access, version control	x	x										
			O2	Documentation should utilise an appropriate format and system of identification	x	x										
			O3	Ensure processes are in place to review and approve new or updated documentation to ensure it is suitable and adequate	x	x										
EXE	**Execution**	**P**	**Develop processes for the Planning and Control of AM activities**		**x**	**x**		**x**						**x**		
			P1	Define process(es) for the planning and control of all AM activities. These activities are outputs of Components F (AM Risk Management process), H (process for developing AM plans) and V (corrective action in the event of failure)	x	x		x								
			P2	Ensure tasks are executed according to standardised methods		x		x								
			P3	Ensure the process is consistent with AM policy, strategy and objectives		x										
			P4	Ensure the process enables resources to be utilised effectively to balance cost, risk and performance		x										

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		Q	**Develop a Management of Change Process**		**x**	**x**										
			Q1	Ensure a process is in place to assess the risks associated with any planned change, permanent or temporary, which could impact on AM performance - before the change is implemented	x	x										
			Q2	Ensure that planned changes are controlled appropriately to mitigate any significant risk	x	x										
			Q3	Review the unintended consequences of any planned change to prevent recurrence	x											
			Q4	Ensure that this process aligns with the requirements of Component F (AM Risk Management process)	x	x										
		R	**Develop an Outsourcing process**		**x**	**x**										
			R1	Determine which AM processes and activities need to be outsourced; define their scope, boundaries and interfaces with the AMS	x	x										
			R2	Define processes for controlling and integrating these outsourced activities into the AMS	x	x										
			R3	Determine who is responsible for managing each outsourced process or activity	x	x										
			R4	Determine how information and knowledge will be exchanged between external service providers and the AMS	x	x										
			R5	Ensure that outsourced resources are sufficiently competent and aware of the AMS, in alignment with the requirements of Components K (AM Awareness) and L (AM Communication)	x	x										
			R6	The performance of outsourced processes and activities should be monitored according to the same requirements as Component S (Performance Measurement)	x											x
EVAL	**Evaluation**	**S**	**Develop processes for Performance Measurement and Reporting**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
			S1	Determine what needs to be measured and how often, defining the process for how results are taken, analysed, evaluated and reported. Measures should include but are not limited to (S2 - S6):	x	x	x	x						x		
			S2	The performance of assets, the AMS and AM activities	x	x	x	x		x						x
			S3	The performance of the AM risk management process (Component F)	x	x										
			S4	Any measures required by key stakeholders, both internally or externally	x	x	x	x								x
			S5	Performance against the AM objectives defined as an output of Component G	x			x		x				x	x	x
			S6	Evidence of AM performance results shall be retained	x	x										
			S7	Ensure the use of a mixture of leading and lagging indicators		x									x	
		T	**Develop an Internal Audit Process**		**x**	**x**	**x**			**x**					**x**	**x**
			T1	Conduct internal audits to determine if the AMS is functioning as intended and if it meets all requirements	x	x				x					x	x
			T2	Develop an internal audit programme to determine the frequency, scope, method and responsibility for each audit	x	x				x						
			T3	Select auditors and conduct audits in a manner which ensures impartiality and objectivity	x	x										
			T4	Ensure that audit results are reported to relevant management and that evidence of the results is retained	x	x										

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		U	**Develop a Management Review Process**		**x**	**x**	**x**			**x**						**x**
			U1	Senior management shall periodically review the AMS to ensure that it remains suitable and effective. Content to be reviewed includes but is not limited to (U2 - U6):	x	x				x						x
			U2	The status of any actions from previous management reviews	x	x										
			U3	Any changes in the organisational context (Component A) that could impact the AMS	x	x	x							x		
			U4	Information on AM performance from Components S (Performance Measurement), T (Internal Audit) and V (Corrective action in the event of failure).	x	x			x			x				x
			U5	Any significant changes to risks identified via Component F (AM Risk Management process)	x									x		x
			U6	The AM Policy to ensure that it is still relevant and consistent with wider organisational requirements	x	x	x						x			
			U7	Appropriate action should be taken by management to address any issues found and to drive improvement of the AMS	x	x				x	x	x		x		
			U8	Ensure that evidence of the decisions and results of management reviews are retained	x	x										
			U9	Ensure that any relevant outputs are considered during reviews of the wider organisational strategy		x										
IMP	**Improvement**	**V**	**Develop a process for determining Corrective Action in the Event of Failure**		**x**	**x**								**x**		
			V1	When there is an incident of poor asset or AMS performance, corrective action should be taken to deal with the immediate consequences and bring the situation under control	x	x										
			V2	After the immediate consequences have been dealt with, evaluate the failure to determine the root cause	x	x										
			V3	Action shall be taken to eliminate the root cause and prevent recurrence elsewhere (the action should be proportionate to the risk of further failure)	x	x										
			V4	Review the effectiveness of any action taken	x											
			V5	Retain appropriate records of past failures, the actions taken and their effectiveness	x	x										
			V6	This process and all of its requirements shall also apply when potential failures are identified proactively	x	x										
		W	**Deliver Continuous Improvement**		**x**	**x**	**x**		**x**	**x**						
			W1	Develop a process to deliver continuous improvement of the AMS and AM performance. This process should identify opportunities for improvement, assess, prioritise, and implement actions and review their effectiveness.	x	x										
			W2	Actively seek new AM practices and technology and evaluate them to establish their potential benefit to the organisation		x										
				Number of codes missing:	**14**	**16**	**97**	**112**	**110**	**89**	**106**	**119**	**115**	**106**	**113**	**93**
				% Complete:	*89*	*88*	*25*	*14*	*15*	*32*	*18*	*8*	*12*	*18*	*13*	*28*

Appendix B – Table showing potential AMS Requirements Frameworks from the literature against the acceptance criteria

Potential AMS RF	1. Compatible AM definition?	2. Defines AMS "requirements" and not "guidance"?	3. Not an AMS based on an already-known framework?	Comment (if acceptance criteria not met)
ISO 55001 (British Standards Institute, 2014b)	✓	✓	✓	
ISO 55002 (British Standards Institute, 2014c)	✓	X	✓	Provides guidance on the application of ISO 55001; does not add any additional AMS requirements.
PAS 55-1 (British Standards Institute, 2008a)	✓	✓	✓	
PAS 55-2 (British Standards Institute, 2008b)	✓	X	✓	Provides guidance on the application of PAS 55-1; does not add any additional AMS requirements.
Life Cycle Engineering's Asset Management System Framework (Life Cycle Engineering, 2014)	✓	X	✓	This article provides guidance on how to implement some of the specific practices required for an AMS aligned to ISO 55001
Asset Management Framework and Guidelines - Western Australia Department of Local Government (Department of Local Government, 2011)	✓	✓	✓	
A framework for the engineering asset management system (El-Akruti and Dwight, 2013)	✓	✓	✓	

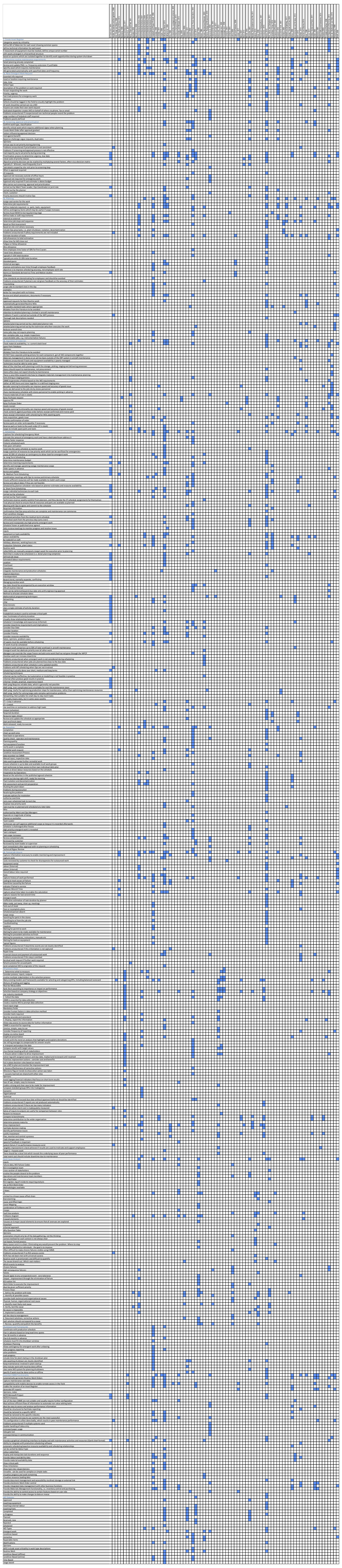
Highway Infrastructure Asset Management Guidance Document (Department for Transport, 2013)	✓	X	✓	Provides guidance on how to implement the requirements of PAS 55 / ISO 55000 in the UK highway infrastructure sector
Total Enterprise Asset Management Quality Framework (Water Environment Research Foundation, 2005)	✓	✓	✓	
Network Rail Asset Management Strategy (Network Rail, 2014)	✓	✓	X	This document forms part of Network Rail's AMS. It is their "AM Strategy" – written in order to comply with the requirements of PAS 55 / ISO 55000
Framework for Asset Management (Asset Management Council, 2014)	✓	✓	✓	
A Framework for Asset Management (Port, Ashun and Callaghan, 2011)	✓	X	✓	Guidance on specific AM practices, rather than AMS requirements
A Framework for Strategic Infrastructure Asset Management (Too, 2010)	✓	X	✓	Provides guidance on AM processes which are important for infrastructure assets, based on a review of current practice.
The Asset Management Landscape (Global Forum on Maintenance and Asset Management, 2014)	✓	X	✓	Provides guidance on 39 specific AM practices ("subject areas"), rather than on AMS requirements
How organisations manage their physical assets in practice (European Federation of National Maintenance Societies, 2012)	✓	X	✓	Describes asset life cycle stages and external influencing factors. Does not define AMS requirements – it refers to PAS 55 for this purpose

Asset Management – an anatomy (Institute of Asset Management, 2014)	✓	X	✓	Aligned to the 39 specific AM practices defined in The AM Landscape, above, and offers similar guidance
Asset Management Overview (US Department of Transportation, 2007)	✓	✓	✓	
Asset Management Framework for Geotechnical Infrastructure (Sanford Bernhardt, Loehr and Huaco, 2003)	✓	X	✓	Based on (an earlier version of) the same model from the US Department of Transportation, above, but adapted specifically to provide guidance for geotechnical infrastructure assets.
Asset Management for Small Water Systems (Washington State Department of Health, 2009)	✓	✓	✓	
The framework for a regional transit asset management system (Yoder and Delaurentiis, 2003)	X	X	X	Framework for an AM software system. Requirements include: "internet enabled; multimedia integrated data warehouse"
Asset life cycle management: towards improving physical asset performance in the process industry (Schuman and Brent, 2005)	✓	X	✓	Describes asset life cycle phases and recommends specific AM practices for each, rather than AMS requirements
Designing an improving asset management system for offshore drilling operations (Riddell, 2008)	X	X	X	Framework for an AM software system. Requirements include: "internet connectivity; reliable software; web application"
Asset management system built from scratch (Kurunsaari, 1999)	X	X	X	Framework for an AM software system. Requirements include: "fully graphical; user-friendly interface"

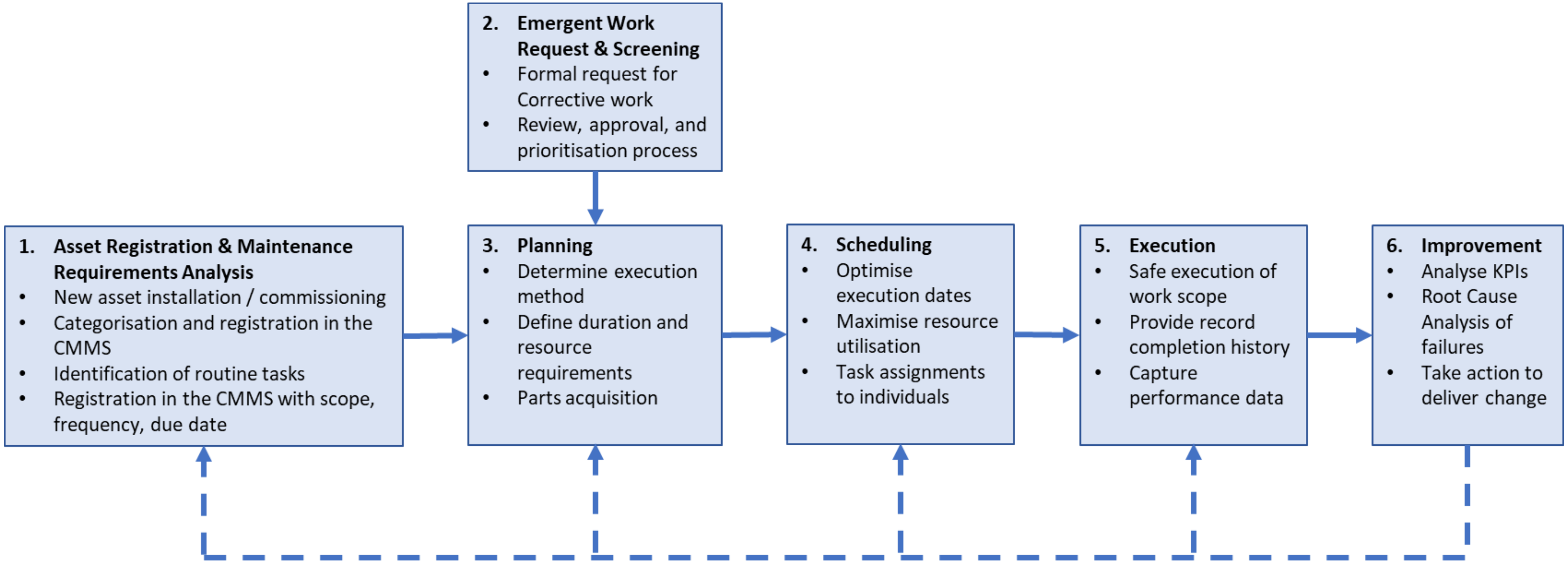
An Integrated Maintenance and Asset Management System (Narayanamurthy and Arora, 2008)	X	X	X	Framework for an AM software system. Requirements include: "advanced diagnostic features; integration with purchase information system"
Asset Management for the Roads Sector (OECD, 2001)	✓	✓	✓	
Asset Management for Sustainable Road Funding (Crist, et al., 2013)	✓	✓	✓	
Development and implementation of an asset management framework for wastewater collection networks (Younis and Knight, 2012)	✓	✓	✓	
Framework model for asset maintenance management (Hassanain, Froese and Vanier, 2003)	X	X	X	Discusses and compares AM software applications
Building an asset management system for electric utilities on a component-based environment (Vetter, Werner and Kostic, 2000)	X	X	X	Defines an AMS as "a set of software applications that support AM activities"
The basic components of an effective asset management program (Mueller and Schulz, 2001)	X	X	X	Discusses AM software: intelligent field devices; asset data communication
Asset Management: Can You Do It Yourself? (Merritt, 2009)	X	X	X	Discusses AM software
Theoretical framework for transportation infrastructure asset management based on review of best practices (Arif and Bayraktar, 2012)	✓	X	✓	Provides guidance on specific AM practices for the transportation infrastructure sector in the US

Key Components for the Effective Management of Airport Assets (Hein, 2014)	X	X	X	Describes an AMS as a database for asset information. Provides detailed AM practices specifically for the airport sector.
Guide to Integrated Strategic Asset Management (Brown et al., 2012)	✓	✓	✓	

Appendix C – Codebook of Maintenance Delivery practices extracted from the literature



A Tailorable Framework of Practices for Maintenance Delivery – Overview



Framework Prefix Section

List of possible maintenance KPIs and their impact on the framework tailoring process

	Performance Measure	Definition	Mandatory CMMS Implementation Requirements	Mandatory Framework Steps
1	**Assets classed as Critical**	Assets with class = critical / Total assets	[Asset Record, Field] Criticality = Critical	1.09
2	**Assets that have routine maintenance in place**	Assets that are included in a Routine Maintenance Call / Total assets	[Routine Maintenance Call, Field] Asset Record ID	1.19
3	**Data completeness**	Asset record number of mandatory fields populated / Required	[Asset Record, Function] Ability to flag fields as mandatory	1.07
4	**Availability loss due to failure**	Hours of plant downtime incurred, if caused by plant failure	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown	5.40 2.04
5	**Availability loss, critical equipment only**	Hours of plant downtime incurred, if Asset Class = Critical	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown [WO Request, Field] Asset Record ID [Asset Record, Field] Criticality = Critical	5.40 2.04 2.04 1.09
6	**Backlog - Average age**	Average time since creation for all outstanding WO Requests	[WO Request, Function] Date, Time created [WO Request, Status] Problem Resolved	2.04 5.41
7	**Backlog - Rate of change**	New WO Requests created - WO Requests Closed in time period	[WO Request, Status] New Request [WO Request, Status] Problem Resolved	2.05 5.41
8	**Backlog - Total**	Quantity of WO Requests outstanding (i.e. not complete)	[WO Request, Status] Problem Resolved	5.41
9	**Defects discovered via preventative inspection**	Quantity of WO Requests with Type = Inspection Based	[WO Request, Field] WO Request Type = Inspection Based	5.36
10	**MTBF or MTTF or reliability**	Operating time period / Quantity of WO Requests created with "Type = Breakdown" during time period	[WO Request, Field] WO Request Type = Breakdown [WO Request, Function] Date, Time created	2.04 2.04
11	**MTTR**	Total downtime incurred / Quantity of breakdowns	[WO Request, Field] Total Downtime Incurred = (hours) [WO Request, Field] WO Request Type = Breakdown	5.40 2.04
12	**Defect Priority Distribution**	Quantity of WO Requests, categorised by Priority	[WO Request, Field] Priority	2.14
13	**Quantity of defects by system**	Quantity of WO Requests, categorised by System / Location	[WO Request, Field] System or Location	2.04, 1.05
14	**Quantity of defects by asset type**	Quantity of WO Requests, categorised by asset type	[WO Request, Field] Asset Type	2.04, 1.09
15	**Quantity of defects by root cause**	Quantity of WO Requests, categorised by root cause	[WO Request, Field] Root Cause	5.40
16	**Number of deferred Routines**	Quantity of WO Requests with Type = Deferral Request	[WO Request, Field] WO Request Type = Deferral Request	4.07
17	**Quantity of breakdowns**	Quantity of WO Requests with Type = Breakdown	[WO Request, Field] WO Request Type = Breakdown	2.04
18	**Repeated maintenance tasks due to poor quality**	Quantity of WO Requests with Type = Rework	[WO Request, Field] WO Request Type = Rework	5.25
19	**Historical average task duration**	Actual time taken to complete a given task, on average	[WO, Field] Actual Duration = (hours)	5.30
20	**Cost of labour**	WO Actual Duration * Labour rate for Work Team	[WO, Field] Actual Duration = (hours) [Work Team, Field] Labour Rate = (£)	5.3

	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Ellis, 1998	Fernandez and Marquez, 2012	Institute of Nuclear Power Operations, 2010	Kidam and Hurme, 2013	Kumar et al., 2013	Modi, 2010	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Seela and Yackel, 2017	Shafeek, 2014	Simões, Gomes and Yasin, 2011	Trindade and Nathan, 2008	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
1											■															
2					■						■															
3											■															
4				■	■					■	■						■		■					■		
5									■																	
6												■														
7		■									■						■									
8	■	■						■	■		■	■					■	■	■					■	■	
9											■															
10		■		■	■		■	■	■		■			■		■	■	■	■					■		
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19											■													■		
20							■	■	■		■			■			■		■							

	Performance Measure	Definition	Mandatory CMMS Implementation Requirements	Mandatory Framework Steps	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Ellis, 1998	Fernandez and Marquez, 2012	Institute of Nuclear Power Operations, 2010	Kidam and Hurme, 2013	Kumar et al., 2013	Modi, 2010	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Seela and Yackel, 2017	Shafeek, 2014	Simões, Gomes and Yasin, 2011	Trindade and Nathan, 2008	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
21	**Cost of Reactive Vs Preventive work**	Cost of labour and materials when WO Type = Reactive, compared to when WO Type = Routine, for all completed work	[WO, Field] Actual Duration = (hours) [Work Team, Field] Labour Rate = (£) [WO, Field] Materials Used = (£) [WO, Field] WO Type = Routine [WO, Field] WO Type = Reactive [WO, Status] Financially Complete	5.30 5.32 1.19 2.18 5.39		■		■				■	■		■															
22	**Cost per asset**	Total cost of all WOs completed against a specific Asset Record, including cost of Labour and Materials	[WO, Field] Actual Duration = (hours) [Work Team, Field] Labour Rate = (£) [WO, Field] Materials Used = (£) [WO, Status] Financially Complete [WO, Field] Asset Record ID	5.30 5.32 5.39 1.19, 2.17																					■					
23	**Cost per maintenance type**	Comparison of cost of labour and materials across all WO Types, for all completed work	[WO, Field] Actual Duration = (hours) [Work Team, Field] Labour Rate = (£) [WO, Field] Materials Used = (£) [WO, Field] WO Type = (various options, user defined) [WO, Status] Financially Complete	5.30 5.32 2.18 5.39					■																					
24	**Hours maintenance executed by contractors**	Time recorded to complete WO, if Work Team Type = Contractor	[WO, Field] Actual Duration = (hours) [Work Team, Field] Type = Contractor	5.30					■		■	■			■															
25	**Hours maintenance executed by plant operators**	Time recorded to complete WO, if Work Team Type = Operations	[WO, Field] Actual Duration = (hours) [Work Team, Field] Type = Operations	5.30					■																					
26	**Hours maintenance executed during overtime**	Time recorded to complete WO, if Work Team Type = Overtime	[WO, Field] Actual Duration = (hours) [Work Team, Field] Type = Overtime	5.30								■											■					■		
27	**Labour utilisation**	Total time recorded against completed WOs / Total time available, per Work Team, per Period	[WO, Field] Actual Duration = (hours) [Work Team, Field] Type = (various) [Work Team, Function] Define working calendar	5.30		■		■	■		■	■	■		■			■			■	■				■		■		
28	**Material costs per WO**	Sum all material costs listed within the WO	[WO, Field] Materials Used = (£)	5.32		■					■		■					■			■		■							
29	**Material stock outs**	Number of instances when Stock Items are requested but stock is unavailable	[Material Record, Field] Material ID Number [Material Record, Field] Stock Level [WO, Field] Materials Required = (Stock Number, Quantity) [WO, Function] Check stock levels of specified materials against required quantities	1.16 1.16 3.09 3.18		■	■				■	■				■					■	■								
30	**Non-stock parts used**	Quantity of materials used without a Stock Number / Quantity of materials used	[Material Record, Field] Material ID Number [WO, Field] Materials Used = (Material ID Number, Quantity)	1.16 5.32			■																							
31	**Planned Vs Actual task duration**	Estimated task duration against Actual recorded time	[WO, Field] Planned Duration = (hours) [WO, Field] Actual Duration = (hours)	3.08 5.30		■		■				■						■				■			■			■		
32	**Ratio of Reactive to Preventative work**	Quantity of completed WOs when WO Type = Reactive, compared to when WO Type = Routine	[WO, Field] WO Type = Routine [WO, Field] WO Type = Reactive [WO, Status] Work Complete	1.19 2.18 5.29	■	■					■	■	■		■	■		■			■	■	■		■				■	

#	Performance Measure	Definition	Mandatory CMMS Implementation Requirements	Mandatory Framework Steps	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Ellis, 1998	Fernandez and Marquez, 2012	Institute of Nuclear Power Operations, 2010	Kidam and Hurme, 2013	Kumar et al., 2013	Modi, 2010	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Seela and Yackel, 2017	Shafeek, 2014	Simões, Gomes and Yasin, 2011	Trindade and Nathan, 2008	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
33	**Schedule loading**	Hours of work scheduled / Hours available, per period, per Work Team	[WO, Field] Planned Duration = (hours) [WO, Field] Scheduled Start Date = (date) [WO, Field] Scheduled Finish Date = (date) [WO, Field] Work Team [Work Team, Function] Define working calendar	3.08 4.06 4.06 3.07																	■				■					
34	**Schedule stability**	% of WOs after Schedule Frozen (or Confirmed) which experience changes to Scheduled Dates, per time period	[WO, Status] Scheduled (Confirmed) [WO, Field] Scheduled Start Date = (date) [WO, Field] Scheduled Finish Date = (date) [WO, Function] Record changes to Scheduled Dates	4.17 4.06 4.06												■														
35	**Schedule delays caused by incomplete job preparation**	Quantify schedule delays per WO (Actual recorded time - Planned time), filtered by Reason Code = Incomplete Job Prep	[WO, Field] Planned Duration = (hours) [WO, Field] Actual Duration = (hours) [WO, Field] Reason Code = Incomplete Job Prep [WO, Function] Reason Code field to become mandatory if Actual Duration exceeds Planned Duration (by tolerance)	3.08 5.30 5.31 5.31												■												■		
36	**Schedule delays caused by waiting for parts**	Quantify schedule delays per WO (Actual recorded time - Planned time), filtered by Reason Code = Waiting for Parts	[WO, Field] Planned Duration = (hours) [WO, Field] Actual Duration = (hours) [WO, Field] Reason Code = Waiting for Parts [WO, Function] Reason Code field to become mandatory if Actual Duration exceeds Planned Duration (by tolerance)	3.08 5.30 5.31 5.31			■																					■		
37	**Schedule delays caused by waiting for purchasing**	Quantify schedule delays per WO (Actual recorded time - Planned time), filtered by Reason Code = Waiting for Purchasing	[WO, Field] Planned Duration = (hours) [WO, Field] Actual Duration = (hours) [WO, Field] Reason Code = Waiting for Purchasing [WO, Function] Reason Code field to become mandatory if Actual Duration exceeds Planned Duration (by tolerance)	3.08 5.30 5.31 5.31																					■			■		
38	**Unplanned parts withdrawals**	Quantify additional materials booked to WO after WO Status = Scheduled (Confirmed)	[Material Record, Field] Material ID Number [WO, Field] Materials Used = (Material ID Number, Quantity) [WO, Status] Scheduled (Confirmed)	1.16 5.32 4.17												■														
39	**WO status distribution**	Quantify the number of WOs at each WO Status	[WO, Status] Various, User defined	Multiple								■										■								
40	**Work completed, by type**	Quantify the number of completed WOs, categorised by WO Type	[WO, Status] Work Complete [WO, Field] WO Type = Various, User defined	5.29 2.18								■			■							■								
41	**WOs close to overdue (in second half of execution window)**	Quantity of WOs where WO Status ≠ Complete, where execution window mid-point is in the past	[WO, Status] Work Complete [WO, Field] Due Date = (date) [WO, Field] Date Created = (date)	5.29 1.24, 2.14 1.24, 2.17												■														
42	**WOs executed on time**	% of WOs where WO Status = Work Complete, and Completion Date does not exceed Due Date, within defined time period	[WO, Status] Work Complete [WO, Field] Due Date = (date) [WO, Field] Completion Date = (date) [WO, Function] Automatically record Completion Date when WO Status is changed to Work Complete	5.29 1.24, 2.14 5.29				■			■	■	■		■	■		■			■	■			■			■		

	Performance Measure	Definition	Mandatory CMMS Implementation Requirements	Mandatory Framework Steps	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Ellis, 1998	Fernandez and Marquez, 2012	Institute of Nuclear Power Operations, 2010	Kidam and Hurme, 2013	Kumar et al., 2013	Modi, 2010	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Seela and Yackel, 2017	Shafeek, 2014	Simões, Gomes and Yasin, 2011	Trindade and Nathan, 2008	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
43	**WOs initiated via inspection**	Quantify WOs which we raised as a result of an inspection, i.e. if WO Type = Condition Based	[WO, Field] WO Type = Condition Based	2.18							■	■													■					
44	**WOs ready for execution**	Quantify the number of WOs with WO Status = Scheduled (Comfirmed)	[WO, Status] Scheduled (Confirmed)	5.14												■														
45	**WOs waiting for parts**	Quantify the number of WOs with WO Status = Awaiting Parts	[WO, Status] Awaiting Parts	3.20											■															

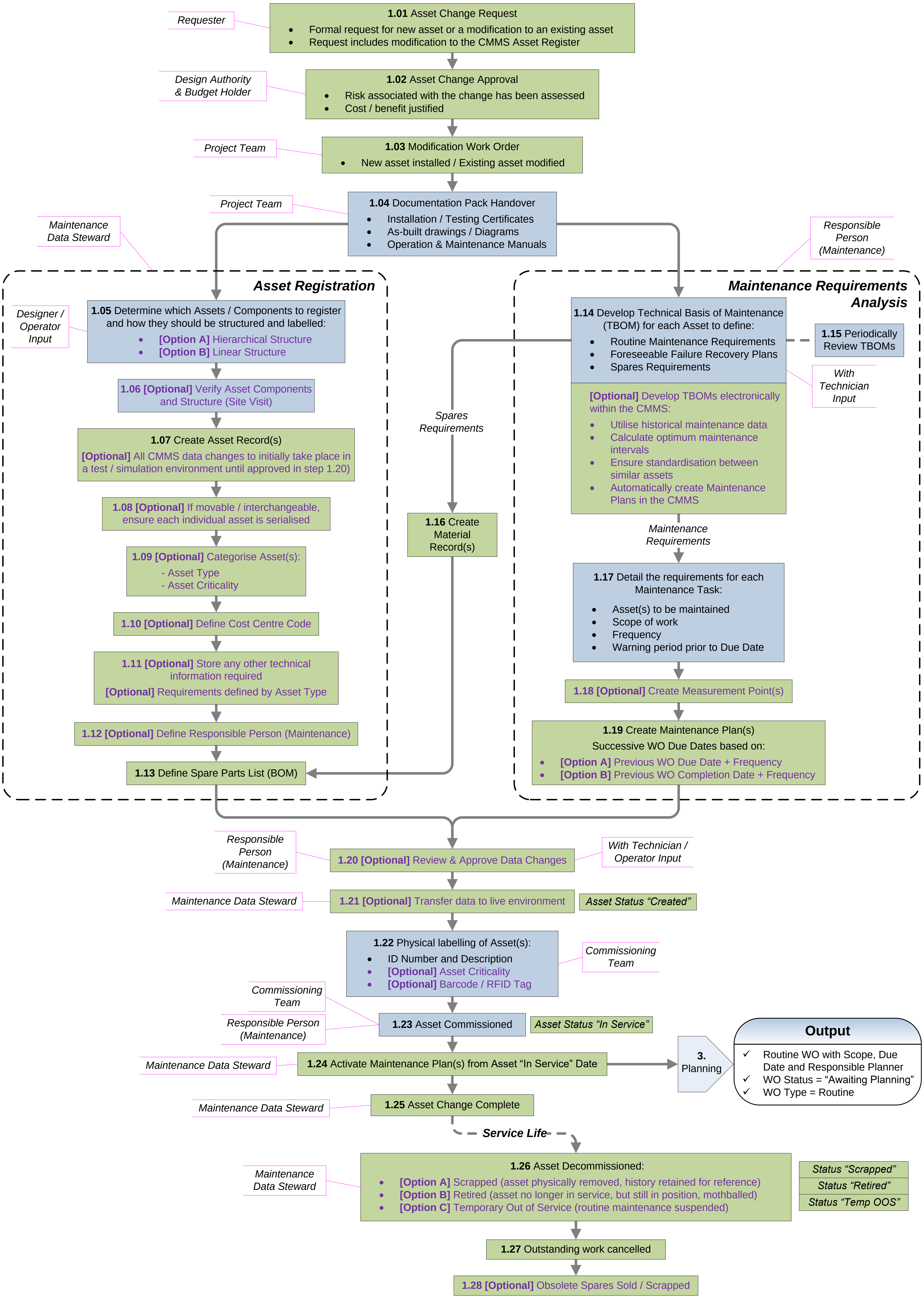
Note that some of the KPIs that were extracted from the literature where determined not to have any impact on the framework tailoring process, because they required data that is not typically available via a CMMS (for example production figures, company profits, salary overheads). Some measures were also excluded because they covered topics that were not within the defined scope of the framework (e.g. inventory management). Each of these rejected KPIs are listed below with a corresponding justification listed alongside it.

	Performance Measure	Unsuitable for data capture via CMMS because:	Arts, Knapp and Mann, 1998	Barry and Stevens, 2011	Barry, Olsen and Petit, 2011	British Standards Institute, 2004	British Standards Institute, 2007	British Standards Institute, 2015a	Campbell and Reyes-Picknell, 2006	Duffuaa and Raouf, 2015	Duffuaa et al., 2001	Fernandez and Marquez, 2012	Kumar et al., 2013	Parida and Chattopadhyay, 2007	Parida et al., 2015	Peters, 2014	Sahoo, 2008	Shafeek, 2014	Westerkamp, 1998	Wulff, 2005
46	**% Maintenance cost consumed by CMMS**	CMMS running costs are captured elsewhere										■								
47	**% of total employees in maintenance**	Employee headcount data is captured elsewhere					■													
48	**% of work carried out via WPC process**	Work executed outside of WPC process is by definition not recorded in CMMS and therefore cannot be quantified		■															■	
49	**% Outsourced personnel**	Employee headcount data is captured elsewhere					■													
50	**Assets that have been analysed for maintenance requirements**	Analysis of Assets is carried out externally to the CMMS (e.g. RCM process)					■					■								
51	**Availability over total maintenance cost**	Some aspects of total maintenance cost (e.g. overheads, salaries, training) are not captured via the CMMS					■													
52	**Average salary**	Salary data is not recorded via the CMMS										■								
53	**Cost for 1 hour of maintenance work**	Some aspects of total maintenance cost (e.g. overheads, salaries, training) are not captured via the CMMS								■	■									
54	**Cost of downtime**	Financial cost of production outages is recorded elsewhere (e.g. production loss accounting system)				■											■	■	■	
55	**Cost of maintenance per unit of production**	Some aspects of total maintenance cost (e.g. overheads, salaries, training) are not captured via the CMMS. Production output is also recorded elsewhere		■			■		■	■		■	■	■	■	■	■			
56	**Cost of overheads, support functions**	Some aspects of total maintenance cost (e.g. overheads, salaries, training) are not captured via the CMMS							■											
57	**Hours spent on training**	A CMMS is not intended for planning training activities										■								
58	**Labour cost over plant capital cost**	Plant capital cost data is not recorded via the CMMS										■								
59	**Labour cost over total maint cost**	Some aspects of total maintenance cost (e.g. overheads, salaries, training) are not captured via the CMMS					■													
60	**Maintenance cost against plant capital replacement cost**	Plant capital cost data is not recorded via the CMMS	■	■			■		■			■			■					
61	**Maintenance cost over energy used**	Energy usage data is not recorded via the CMMS					■													
62	**Maintenance costs as a % of total production cost**	Production costs are not recorded via the CMMS		■									■		■					
63	**Maintenance value received against cost**	Financial value produced by maintenance is not recorded via the CMMS												■					■	
64	**Number of injuries or environmental incidents due to maintenance**	Injuries and environmental incidents are not recorded via the CMMS					■													
65	**Overall Equipment Effectiveness**	Production rate data is not recorded via the CMMS		■				■	■	■		■	■	■	■	■	■			
66	**Overall maintenance cost against budget**	Some aspects of total maintenance cost (e.g. overheads, salaries, training) are not captured via the CMMS									■	■			■	■				
67	**Plant income over asset value**	Plant income and asset value are not recorded via the CMMS										■								
68	**Product rejects due to maintenance**	Product rejection data is not available via a CMMS								■										
69	**Production rate index**	Production rate data is not recorded via the CMMS		■																
70	**Ratio of assets per worker**	Employee headcount data is captured elsewhere										■								
71	**Revenue against maintenance cost**	Revenue data is not available via a CMMS	■																	■
72	**Savings achieved due to improvements**	Financial savings are not recorded via a CMMS														■				
73	**Total Man hours used for planning**	Hours spent planning is not recorded via a CMMS					■													
74	**Training costs over number of people**	Training cost data is not available via a CMMS					■													
75	**Inventory accuracy**	Inventory Management is not within the scope of MD														■				
76	**Inventory turnover or Obsolescence**	Inventory Management is not within the scope of MD		■	■		■		■	■		■	■		■	■			■	
77	**% Value of inventory that doesnt move**	Inventory Management is not within the scope of MD										■								
78	**Inventory value now over inventory value last year**	Inventory Management is not within the scope of MD		■																
79	**Inventory value over asset value**	Inventory Management is not within the scope of MD			■		■					■								
80	**Materials cost over maintenance cost**	Inventory Management is not within the scope of MD					■			■										
81	**Parts quality**	Inventory Management is not within the scope of MD			■															
82	**Stock value to plant capital cost ratio**	Inventory Management is not within the scope of MD																		
83	**Value of inventory**	Inventory Management is not within the scope of MD								■			■			■	■	■		

List of essential CMMS functionality that is necessary in all contexts

	Al-Turki et al., 2014	Barry et al., 2011	Canaday, 2008	Canaday, 2011	Duffuaa and Raouf, 2015	Emmanouilidis et al., 2009	Fernandez and Marquez, 2012	Ismail, 2014	Peters, 2014	Samaranayake and Kiridena, 2012	Shafeek, 2014	Arts, Knapp and Mann, 1998	Campbell and Reyes-Picknell, 2006	Howard, 2004	Keizers, Bertrand and Wessels, 2003	Kherun et al., 2002	Lorenzi, 2017	Sahoo, 2008	Suttell, 2005	Swanson, 1997	US Department of the Army, 2013	Westerkamp, 1998	Wulff, 2005
Automatically generate Routine Work Orders					X				X				X					X	X	X	X	X	
Capture maintenance cost data					X								X										
Compatibility with mobile devices to enable remote access in the field		X			X	X	X	X	X				X				X		X				
Enable the creation of an Asset Register					X			X					X					X			X		
Generate KPI reports																	X	X	X	X		X	
Must be easy to access and analyse performance information											X					X		X	X				
Simple, intuitive and easy to use					X		X									X		X					
Provide document management and accessibility via direct storage or external link					X				X									X					
Provide electronic Work Order control					X						X		X			X			X	X			
Provide integrated data management with other business functions	X				X		X				X	X						X	X				X
Provide Materials Management functionality, i.e. inventory control and purchasing			X		X		X						X					X	X	X			
Provide the ability to control access to certain features based on user role														X		X	X						
Provide the ability to make changes to data en masse									X														
Provide a graphical scheduling interface with the following functionality:	X	X			X				X				X		X						X		
Display and edit maintenance activities and resources (Gantt chart format)	X	X			X				X				X		X						X		
Ability to integrate with production scheduling software											X												
Automatic scheduling based on resource availability and scheduling relationships																		X					
Can be sorted by labour type					X																		
Colour coded bars	X																						
Display and manipulate task durations and sequence	X				X					X			X										
Provide labour availability data			X		X					X	X		X										
Provide material availability data										X													
Show critical path	X				X								X										
Show milestones					X																		
Show task inter-dependancies	X				X								X										
Versatile - can be used for complex or simple tasks													X										
Visualise progress and work remaining	X														X								
Visualise resource loading data	X												X		X								

Framework Section 1 – Asset Registration & Maintenance Requirements Analysis



Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.01 Asset Change Request	A formal request is made for the installation of a new asset or the modification of an existing asset. A corresponding change to the CMMS Asset Register is also included in this request. It is good practice to control such requests via a specific WO Request Type (e.g. "Asset Change Request"), which can then be formally reviewed and approved by the relevant responsible person; this will also provide a permanent record of the change for audit purposes (Anonymous Expert 2, 2017; Anonymous Expert 6, 2017).	Physical plant / asset changes are normally subject to a Change Management Process with formal request and approval required by a competent authority (British Standards Institute, 2004). CMMS data changes should also be included in this process, so that the Asset Register is always kept up to date with any plant / asset modifications. This process should include the installation of new assets or changes to existing assets.	[WO Request, Field] Type = Asset Change Request
1.02 Asset Change Approval	The proposed change is reviewed and either approved or rejected. The Design Authority should ensure that any risks associated with the change have been adequately assessed, and the Budget Holder should review the proposal from a cost / benefit perspective. Approval is required from both persons before the change is sanctioned.		[WO Request, Status] Approved [WO Request, Status] Rejected
1.03 Modification WO	A Modification WO is created from the approved change request. This is used to plan and control the change activity, i.e. the asset installation or modification. This WO could be managed alongside other maintenance tasks (particularly if maintenance resources are utilised), or via a separate project process, depending on the scale of the task and the structure of the organisation.		[WO, Field] WO Type = Modification [WO, Function] Creation only possible via an approved WO Request
1.04 Documentation Pack Handover	The project team responsible for the change activity formally hand over all necessary documentation to the maintenance team (British Standards Institute, 2015a).	When new assets are installed, the Project Team responsible must hand over all of the new asset's records and documentation to the maintenance team (e.g. installation / testing certificates, as-built drawings / diagrams, data sheets, operation and maintenance manuals etc.). This information will be required to set up the asset in the CMMS, and determine spares holdings and maintenance requirements (British Standards Institute, 2004).	N/A

Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.05 Determine which Assets / Components to register and how they should be structured and labelled	Before adding assets to the CMMS Asset Register, determine which components to include (i.e. the level of detail) and the most appropriate structure and labelling system (British Standards Institute, 2015a).	To structure assets effectively, it is helpful to take input from someone with in-depth knowledge of how the asset is designed and operated (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017).	
	Regarding the level of detailed required:	• Most experts advocate registering every maintainable component (e.g. valve, instrument); this allows each item to be categorised separately so that critical components are more visible, and have their own individual maintenance history (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). • However, be aware that because the creation of this data is a huge use of time and resources, this effort can be prioritised if necessary. For critical systems (i.e. those which have the potential to impact objectives upon failure) it may be appropriate to register all components in detail, but for non-critical systems it is acceptable to register only the major items (Anonymous Expert 4, 2017).	
	Regarding structure, the following options are available: • **[Option A]** Arrange assets into a hierarchical, systemised structure (e.g. Plant > Facility > System > Sub-system > Major Asset > Minor Asset) (Shaw, 1998; Peters, 2014; British Standards, Institute, 2015a).	This approach enables a logical drill-down through the structure to locate the lower-level components (Peters, 2014). This makes it easier for end-users to locate the correct Asset Record without knowing its ID number (Anonymous Expert 7, 2017; Anonymous Expert 10, 2017). Systemisation also helps to identify opportunistic maintenance opportunities during system shutdown (Institute of Nuclear Power Operations, 2010).	[Asset Record, Function] Ability to sort records into a hierarchical structure, i.e. parent-child relationships
	• **[Option B]** Arrange assets into a linear structure (i.e. distinguish those which are adjacent / part of a sequence).	Applicable for linear assets (e.g. roads, railways, runways). Consider that such assets may be registered in say 100m sections, and the CMMS will need to know which assets are adjacent to each other, i.e. the sequence in which they are arranged, in order to plan inspections and pinpoint the location of defects. Be aware that linear assets may require a combination of both option A and option B (Anonymous Expert 10, 2017).	[Asset Record, Function] Ability to sort records into a linear structure, i.e. sequential relationships
	Regarding labelling, Asset Record IDs must be unique and should reflect the asset's position in the structure.	It is beneficial for Asset Record ID numbers to be created according to a formal, standardised numbering system, which is coded so that each character carries a defined meaning (as opposed to a random number); this helps to establish a common understanding throughout the business, which is particularly useful in multi-site scenarios (Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017). International standards are available, such as the German "KKS" numbering system, developed for the power generation sector (Siemens, 2010).	[Asset Record, Field] ID Number [Asset Record, Function] ID Numbers must be unique [Asset Record, Function] Define labelling format [Asset Record, Field] Description
1.06 [Optional] Verify Asset Components and Structure (Site Visit)	Conduct a site visit to survey the new asset(s) and ensure that all components are genuinely installed before they are included in the CMMS.	This is particularly necessary in contexts where large quantities of new assets are installed at once (e.g. a new-build scenario), to ensure that the CMMS Asset Register accurately reflects the as-built configuration. Even small mistakes can lead to maintenance requirements being unintentionally omitted, which can have serious consequences for reliability or safety (drawings should never be completely relied upon, as they could be incorrect or out of date) (Anonymous Expert 7, 2017).	N/A

Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.07 Create Asset Record(s)	Asset Records are created to represent the new asset(s) in the CMMS (British Standards Institute, 2004; Campbell and Reyes-Picknell, 2006; Sahoo, 2008; US Department of the Army, 2013; Ismail, 2014). **[Optional]** Most industry experts agree (see submission 6, section 3.2.1) that all data changes should initially take place in a test / simulation environment only. Transfer to the live CMMS environment should only take place once the proposed changes have been reviewed and approved by a responsible person (i.e. step 1.20).	If an asset is not represented in the CMMS, then maintenance activities carried out on that item cannot be recorded or managed effectively. Authorisation to create or make changes to asset data within the CMMS should be tightly controlled, and only possible for a small number of trained and competent people (i.e. "Data Stewards"). This is to prevent malicious or accidental damage to data (Anonymous Expert 7, 2017; Anonymous Expert 9, 2017).	[CMMS, Function] Simulation / Test Environment [Asset Record, Function] Restrict access to make changes to authorised persons only
1.08 [Optional] If movable / interchangeable, ensure each individual asset is serialised	For assets which, upon failure, will be removed, maintained and potentially installed in a different location, it is necessary to provide a unique serial number for the asset, in addition to the Asset Record ID (which just represents the asset's location).	This functionality allows the CMMS to track the movement of assets, which is only necessary for those which may be removed, repaired, and later installed in a different location (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 10, 2017). This ensures that the maintenance history for the asset is recorded, even if its location changes (US Department of the Army, 2013; Peters, 2014, Duffuaa and Raouf, 2015). This step is optional because not all contexts will feature movable assets.	[Asset Record, Function] Serialised Assets
1.09 [Optional] Categorise Assets	Each Asset Record can be categorised, generally in two ways:		
	- Asset Type (e.g. pump, fan, motor) (British Standards Institute, 2015a).	The categorisation of assets by Asset Type is useful: - For filtering and sorting breakdown data, so that the performance of similar equipment can be analysed and compared (Institute of Nuclear Power Operations, 2010; Anonymous Expert 3, 2017); - When defining maintenance requirements, to ensure that similar equipment have equivalent routine maintenance in place (Anonymous Expert 9, 2017).	[Asset Record, Field] Asset Type = (various, depending on user context)
	- Asset Criticality (e.g. Production Critical, Safety Critical) (Sahoo, 2008; US Department of the Army, 2013; Instiute of Nuclear Power Operations, 2010).	It is useful to categorise assets based on risk, as this helps to prioritise any WOs raised against those assets (Institute of Nuclear Power Operations, 2010). Relevant categories of risk include: • How will their failure impact safety / health / environment? (Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 10, 2017; Anonymous Expert 12, 2017). • Which regulatory obligations will be breached if inspections are late? (Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 8, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017). • How will their failure impact production (i.e. level of redundancy – is there an installed standby)? (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 12, 2017) • Does their failure carry a financial risk? (Anonymous Expert 8, 2017) • How will their failure impact corporate reputation? (Anonymous Expert 8, 2017)	[Asset Record, Field] Criticality = (various, depending on user context)

Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
	It is important that the Criticality rating of the asset is clearly visible within any WO Requests or WOs raised against that asset. This information is essential during work prioritisation, to highlight the importance of the work and the potential consequences if it is not carried out on time (e.g. a breach of legal compliance or potential plant breakdown) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).		[WO, Field] Asset Criticality = (copied from Asset Record)
1.10 [Optional] Define Cost Centre Code	The asset is assigned a Cost Centre code (Cooper, 1998; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017).	Most industry experts agree (see section 7.5) that each Asset Record should be assigned a Cost Centre code. This information will need to pull through to any WOs raised against that asset, so that maintenance costs are booked to the correct Cost Centre. Costs are typically divided up based on area, production stream, project, or discipline.	[Asset Record, Field] Cost Centre [WO, Field] Cost Centre = (copied from Asset Record)
1.11 [Optional] Store any other technical information required	CMMS packages are typically capable of storing various technical details against each Asset Record, e.g. manufacturer, model, size, installation date (Sahoo, 2008; US Department of the Army, 2013; Duffuaa and Raouf, 2015).	Be aware that, whilst a large amount of additional reference information can be stored in the CMMS against each asset, this data can be difficult and time consuming to create, manage and keep up to date – therefore effort should only be expended creating data if it will serve a useful purpose later (i.e. if specific searching / filtering of data is required); it may be more appropriate to simply provide links to relevant drawings, manuals or data sheets instead (Anonymous Expert 1, 2017; Anonymous Expert 7, 2017; Anonymous Expert 9, 2017).	[Asset Record, Field] Technical Details (various formats and units), depending on user requirements
	With some CMMS packages, it is possible to configure the system to automatically create a set of pre-defined technical information fields for a new asset, based on its Asset Type selection. This reduces workload and ensures consistency (Anonymous Expert 11, 2017).		[Asset Record, Function] Automatically create technical information fields based on Asset Type selection
1.12 [Optional] Define Responsible Person (Maintenance)	The person who is responsible for the asset (in a maintenance life-cycle context), its performance and any associated decision making is recorded in a specific field within the Asset Record. Depending on the industry sector, this person may be called a Responsible Engineer / Technical Authority / Asset Manager etc.	This makes it easier for users to see who is responsible for approving any TBOMs (see step 1.14), change requests, or deferral requests for that asset (Anonymous Expert 7, 2017). This option is applicable in contexts where there are multiple responsible persons across the asset portfolio, and it is therefore worthwhile making specific responsibility more visible within the CMMS.	[Asset Record, Field] Responsible Person
1.13 Define Spare Parts List (BOM)	Each Asset Record should have a Spare Parts List defined (often called a Bill of Materials or BOM), which provides links to each Material Record associated with the asset (British Standards Institute, 2004; US Department of the Army, 2013; Peters, 2014; Duffuaa and Raouf, 2015).	Providing links to critical or frequently used spares removes the need for planners to search the materials database manually when planning WOs, which saves time and reduces human error.	[Asset Record, Function] Spare Parts List (BOM) providing links to relevant Material Records [Material Record, Function] Assign to Spare Parts List (BOM)

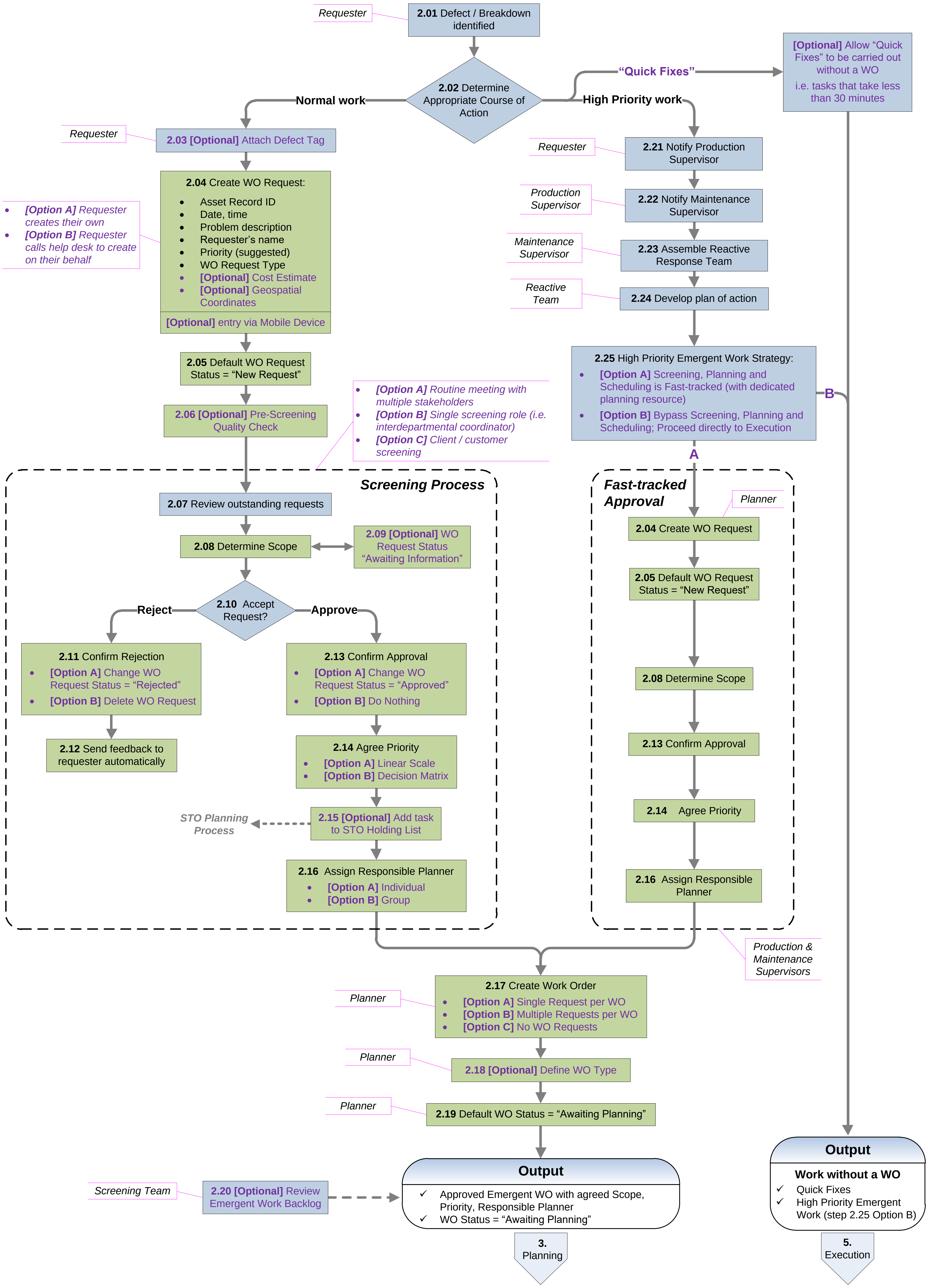
Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.14 Develop Technical Basis of Maintenance (TBOM) for each Asset	Ensure that a TBOM is developed for each asset, i.e. a formal document defining its routine maintenance and spares requirements (more commonly known as a "Maintenance Plan" – however this term was avoided to prevent duplication with the CMMS entity of the same name, featured in step 1.19) (British Standards Institute, 2004; Fairbairn, Zaal and Wilson, 2013; British Standards Institute, 2015b). TBOMs should also include recovery plans to facilitate a response in the event of foreseeable failures (i.e. emergent work tasks – see section 2) (Anonymous Expert 4, 2017; Anonymous Expert 7, 2017).	The selection of an appropriate methodology for developing TBOMs is outside of the scope of this framework (as defined in submission 4, section 3.6.1); this is a separate Asset Management subject (i.e. reliability engineering) that could warrant a research project in its own right (Global Forum on Maintenance and Asset Management, 2014). However, the activity Itself, along with its key outputs, are included here because they feed forward into the rest of the framework. Whilst it is the role of the Responsible Person (Maintenance) to lead the development of TBOMs, it is helpful to involve technicians in the process as well; this will build more trust in the outcome, especially if there is ever a change in maintenance scope or inspection intervals (Anonymous Expert 11, 2017). The asset's criticality rating (as defined in step 1.09) can help to determine the depth of analysis and consequently the extent of the maintenance required (British Standards Institute, 2015a; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 12, 2017).	
	[Optional] some CMMS packages provide functionality allowing TBOMs to be developed and held electronically within the CMMS (or via third party software that interfaces with the CMMS), which has the following advantages: - Historical maintenance data can be fed directly into the analysis: e.g. Mean Time Between Failure (MTBF) data for each failure mode. Some packages can even provide MTBF data from other sites and companies that use the same equipment; - Optimum inspection intervals can be calculated automatically based on this data; • If a new asset is similar to a previously installed one, then the existing plan can be re-used to ensure standardisation; • The outcomes of the analysis can be utilised to automatically create CMMS Maintenance Plans (i.e. step 1.19) (Anonymous Expert 2, 2017; Anonymous Expert 11, 2017).		[CMMS, Function] TBOM Development and Storage [CMMS, TBOM] Provide historical maintenance data (MTBF) [CMMS, TBOM] Calculate Optimum Maintenance Intervals [CMMS, TBOM] Save and re-use plans [CMMS, TBOM] Automatic creation of Maintenance Plans
1.15 Periodically review TBOMs	Review each TBOM periodically, or in the event of a significant failure (British Standards Institute, 2004; Anonymous Expert 1, 2017; Anonymous Expert 4, 2017).	The purpose of a TBOM review is: • to determine if the frequency of Routine Work can be extended, without reducing asset performance – i.e. to achieve the optimum balance between cost and reliability (Sahoo, 2008; Institute of Nuclear Power Operations, 2010; US Department of the Army, 2013; Peters, 2014; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). • to determine if the asset is on course to reach its design life expectancy – i.e. when will capital investment be required for asset renewal (British Standards Institute, 2015a; Anonymous Expert 4, 2017)?	
1.16 Create Material Records	A Material Record is created for each spare part requirement identified in the TBOM. The procurement, receipt and storage of these materials is managed via a separate Materials Management (MM) process, which is outside of the scope of this framework.	Any material that is purchased, stored or utilised for maintenance purposes will require a Material Record in the CMMS, to provide it with a full specification including: - Material ID number; - Description; - Stock level; - Storage Location (Anonymous Expert 7, 2017).	[Material Record, Field] Material ID Number [Material Record, Field] Description [Material Record, Field] Stock Level [Material Record, Field] Storage Location

Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.17 Detail the requirements for each Maintenance task	Specify the following key parameters for each task featured on the TBOM: - Asset(s) to be maintained - Scope of work - Frequency - Warning Period prior to Due Date - Measurement point(s) (if the task is a condition monitoring task – see step 1.18)	These details will be needed to create a Maintenance Plan for each task in the CMMS (see step 1.19), so that a suitable WO is periodically created (Keizers, Bertrand and Wessels, 2003; Wulff, 2005; Sahoo, 2008; British Standards Institute, 2009; Ismail, 2014; Anonymous Expert 2, 2017; Anonymous Expert 6, 2017; Anonymous Expert 11, 2017).	
1.18 [Optional] Create Measurement Point(s)	If the task requires measurements to be taken (e.g. during inspection / condition monitoring activities) then corresponding Measurement Point(s) must be created in the CMMS.	A Measurement Point represents a physical location where measurements are taken, which can be linked to an Asset Record in order to record measurements related to that asset (e.g. oil temperature). It allows measurement parameters to be defined (i.e. data format, units of measurement, upper and lower tolerance bands) and enables readings to be recorded and trended over time (Anonymous Expert 11, 2017).	[Measurement Point, Field] ID Number [Measurement Point, Field] Description [Measurement Point, Field] Data Format (e.g. quantitative, qualitative) [Measurement Point, Field] Units of measurement [Measurement Point, Field] Upper Tolerance [Measurement Point, Field] Lower Tolerance [Measurement Point, Field] Associated Asset Record [Measurement Point, Function] Enable recording of measurements and trending over time
1.19 Create Maintenance Plan(s)	Maintenance Plan(s) are set up in the CMMS for each task specified in the TBOM, incorporating the task parameters specified in step 1.17 and the Measurement Point(s) from step 1.18. This will ensure that WOs are automatically created by the CMMS at the correct frequency and with the required scope, for each routine maintenance requirement. Each WO created in this manner should have the WO Type "Routine" by default, so that routine work can be categorised and quantified (Monsanto, 2007; Barry and Stevens, 2011; Fernandez and Marquez, 2012; Duffuaa and Raouf, 2015). It is also important that a named individual is specified within each WO, with responsibility for planning and progressing the work in a timely manner (see step 2.16).	This is a standard approach for managing routine maintenance tasks via a CMMS (Swanson, 1997; Sahoo, 2008; British Standards Institute, 2009; Baker, Booth and Wilson, 2013; Ismail, 2014; Ramskill, 2014). Industry experts agree (see submission 6, section 3.2.1) that before entering service, new assets should have all of their maintenance requirements defined and set up in the CMMS, so that all required inspections and maintenance are in place from day one – to ensure that maintenance requirements are not missed in early life. This forms part of the formal commissioning process – i.e. the asset is not signed off until the CMMS has been updated with adequate Routine Maintenance. There are two options regarding how Due Dates are calculated for each successive WO (Liebstuckel, 2012): - **[Option A]** Previous WO Due Date + Frequency. Using the example of an annual inspection, this approach means that the inspection will be due on the same date every year; the completion date is not taken into account when calculating the Due date of the next inspection. - **[Option B]** Previous WO Completion Date + Frequency. Using the same example, this approach means that the next inspection will be due 12 months after the previous one was completed. If the inspection is completed early one year, it will be due earlier the next year, so that a maximum of 12 months elapses between inspections.	[Maintenance Plan, Fields] Asset Record ID(s), Description, Frequency, Warning Period prior to Due Date, Responsible Planner [Maintenance Plan, Function] Automatically generate WOs periodically with specified Asset Record ID, Description, Frequency, Warning Period and WO Type = Routine [Maintenance Plan, Function] Due Date of each successive WO to be equal to previous WO Due Date + Frequency [Maintenance Plan, Function] Due Date of each successive WO to be equal to previous WO Completion Date + Frequency

Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.20 [Optional] Review and Approve Data Changes	Key stakeholders review and approve the changes made to the CMMS (i.e. the new Asset Record(s) and Maintenance Plan(s)). For the purposes of the review, all data changes so far take place in a test / simulation environment only; data will be transferred to the live CMMS environment once approval is granted (i.e. step 1.21).	Most industry experts agree (see submission 6, section 3.2.1) that key stakeholders should review and approve any CMMS data changes before they are made permanent: • The Responsible Person (Maintenance) should ensure that the hierarchy structure is logical and accurately reflects the plant configuration. They should also ensure that all asset categorisations / criticalities are correct; • A technician / operator should check that the asset ID number and description make sense from an end-user perspective. A formal record of these approvals should be kept to provide traceability; this can be achieved via a "Data Changes Accepted" status within the associated Asset Change Request that was created in step 1.01.	[WO Request, Field] Type = Asset Change Request [WO Request, Status] Data Changes Accepted
1.21 [Optional] Transfer Data to Live Environment	The approved Asset Record and Maintenance Plan changes are transferred into the live CMMS environment. The new Asset Record(s) have the Asset Status "Created".	This method protects the live environment from errors and ensures good data quality. Poor quality CMMS data wastes time and increases risks to performance and safety.	[CMMS, Function] Transfer of data from Simulation to Live environment [Asset Record, Status] Created
1.22 Physical Labelling of Asset(s)	The asset is physically labelled in the field, consistently with its CMMS Asset Record ID (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 10, 2017). This physical labelling activity should be carried out by the commissioning team as a standard procedure before the asset enters service (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017).	If plant labels are not consistent with CMMS Asset Record IDs and Descriptions, then this can cause: - Defects to be reported against the wrong CMMS Asset Record (which leads to inaccurate data and re-work during planning) (Anonymous Expert 3, 2017; Anonymous Expert 7, 2017). - Maintenance to be carried out on the wrong piece of equipment (which can lead to serious safety risks if that equipment is still live) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017). It is good practice to periodically audit plant labels against the corresponding CMMS Asset Record to ensure consistency – e.g. during Shutdown / Turnaround / Outage (STO) events (Anonymous Expert 5, 2017). **[Optional]** Physical plant labels can also indicate the asset's criticality rating (perhaps via a colour-coding system or using hazard symbols) to assist those in the field in gauging the impact of any failures or defects (Anonymous Expert 4, 2017). **[Optional]** Asset Labels can also include a barcode / RFID (Radio Frequency Identification) tag so that they can be scanned with a mobile device, to provide location data during a maintenance task or defect report. This is only applicable in contexts where the CMMS is available on mobile devices (Anonymous Expert 10, 2017).	[CMMS, Function] Barcode / RFID scanning interface [CMMS, Function] Mobile device compatibility
1.23 Asset Commissioned	The commissioning process is completed, including acceptance and sign off of the new asset by the Responsible Person (Maintenance). The asset is formally handed over from the Commissioning Team and is allowed to enter service. The Asset Status is changed from "Created" to "In Service" in the CMMS.	Industry experts strongly agree (see submission 6, section 3.2.1) that new assets should only be accepted by the Responsible Person (Maintenance) when all of the following are complete, i.e.: - The asset has been installed and tested (i.e. step 1.03). - All relevant documentation has been handed over (i.e. installation / testing certificates, as-built drawings / diagrams, data sheets, operation and maintenance manuals) (i.e. step 1.04). - The CMMS Asset Register has been updated with all new asset information (i.e. step 1.07 – 1.13). - A TBOM has been developed for all new asset(s) (i.e. step 1.14). - Maintenance Plan(s) have been created for all tasks specified in the TBOM (i.e. step 1.19). - Asset labelling is complete and consistent with the CMMS (1.22).	[Asset Record, Status] In Service

Process Step	Definition	Justification / Guidance	CMMS Implementation Spec.
1.24 Activate Maintenance Plans from Asset "In Service" Date	Now that the Asset's "In Service Date" is known, all associated Maintenance Plans (created in step 1.19) can now be activated (British Standards Institute, 2015a).	Industry experts agree (see submission 6, section 3.2.1) that maintenance responsibilities begin on "day one" of an asset's service life – i.e. its "In Service Date". Therefore, all associated Maintenance Plans are set up to count from this date, so that they automatically create WOs at the correct intervals (e.g. the first annual inspection should be due exactly 365 days after the "In Service Date"). Refer to the flowchart arrow that references forward to section 3, where all "called" WOs will be planned in detail.	[Maintenance Plan, Field] Start Date [Maintenance Plan, Function] Due Date of the first WO called to be equal to the Start Date plus the specified Frequency
1.25 Asset Change Complete	The Asset Change Request that was raised in step 1.01 is closed out.	Because the asset change process is now complete: the new asset(s) have been commissioned, and the CMMS has been updated with new Asset Record(s) and Maintenance Plan(s).	[WO Request, Status] Closed
1.26 Asset Decommissioned	When an asset reaches the end of its service life, the Asset Record's status is changed to reflect this.	Industry experts agree (see submission 6, section 3.2.1) that the following Asset Status options should be made available to suit different decommissioning circumstances (where applicable depending on the context): • **[Option A] Scrapped**: The asset has finished service and has been removed from site. Maintenance history is retained for reference, but no further WO Requests or WOs can be raised. • **[Option B] Retired in Situ:** The asset is no longer in service, but is still present on site because it cannot be safely / cost effectively removed. Periodic inspections must still be carried out for safety reasons (e.g. to prevent structural collapse, or to prevent environmental contamination). • **[Option C] Temporarily Out of Service:** Asset is not currently in service, but may be reinstated in the future. Routine maintenance requirements are suspended.	[Asset Record, Status] Scrapped (prevent further WO creation) [Asset Record, Status] Retired in Situ [Asset Record, Status] Temporarily Out of Service (prevent WO creation within defined date range)
1.27 Outstanding Work Cancelled	Any open WOs, WO Requests, or Maintenance Plans associated with the decommissioned asset should be cancelled, as they are no longer needed (unless the "Temporarily Out of Service" status is selected as above, in which case the maintenance would be postponed until after the reinstatement date). Ideally, the CMMS would be capable of identifying and cancelling such WOs automatically (Anonymous Expert 11, 2017).	These WOs are no longer relevant because the asset is no longer in service.	[Asset Record, Function] Cancel associated work if Asset Status = Scrapped / Retired in Situ [Asset Record, Function] Postpone associated work if Asset Status = Temporarily Out of Service
1.28 [Optional] Obsolete Spares Sold / Scrapped	Most industry experts agree (see submission 6, section 3.2.1) that any obsolete spare parts that were associated with the decommissioned asset should be identified and either sold off or scrapped (British Standards Institute, 2015a).	Parts that are no longer needed and will never be used should not be held as inventory – time, money and warehousing space would be wasted in storing them. They could also hold some value that could potentially be recovered.	[Material Record, Field] Stock Level

Framework Section 2 – Emergent Work Request & Screening



Process Step	Definition	Justification	CMMS Implementation Spec.
2.01 Defect / Breakdown identified	An asset has failed in service; there is either a complete loss of function (Breakdown) or a partial loss of function (Defect).	The MD process must be capable of managing corrective actions in response to failure, as discussed in submission 4, section 3.3. This step provides an input into the process for such events.	N/A
2.02 Determine Appropriate Course of Action	The person who discovered the failure makes an initial assessment of the situation to determine the next course of action.	The appropriate response depends on the nature of the failure, which will fall into one of the following categories: • **Normal Work** – the vast majority of failures should fall into this category, e.g. generic defects and non-critical breakdowns. The full screening process should be followed as indicated on the flowchart. • **High Priority Emergent Work** – these failures need to be addressed more urgently and therefore follow a different process (e.g. a critical asset failure resulting in a production stop or a safety / environmental / legal risk). • **Quick Fixes [Optional]** – In some contexts, tasks that take less than 30 minutes to execute may be permitted to completely bypass the normal screening process and proceed directly to execution. No Work Order (WO) is required; technicians can go ahead and resolve them autonomously (Hickman, 2011; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 8, 2017). See below for detailed arguments for and against this.	N/A
	Arguments for and against allowing "Quick Fixes" to be carried out without a WO, essentially allowing the screening, planning and scheduling processes to be bypassed for quick and simple tasks.	The process for screening Emergent Work requests is a vital part of work control, ensuring that only valid requests are approved for execution (and consequently the consumption of limited resources, which must be allocated wisely) – the key principle is that no work can go ahead without a WO, and a WO can only be created via an approved WO Request that has been through the formal screening process (involving review by all necessary stakeholders) (Anonymous Expert 5, 2017; Anonymous Expert 11, 2017). These rules ensure the validity of all work entering the system, and ensure that resources are allocated according to agreed priorities. If "Quick Fixes" are allowed to bypass these rules, then it undermines the entire process because resources are not carrying out the work that was agreed; this ultimately results in poor maintenance performance (Shafeek, 2014). However, there are some experts who say that tasks that require less than 30 minutes to execute should be an exception (see submission 6, section 3.2.3). In infrastructure / utilities contexts where work is executed at very remote locations, if a defect is found (often during a routine inspection) it is more practicable to address it there and then, to avoid a return visit – a WO can always be recorded in the system retroactively, ensuring that work history is still recorded (Hickman, 2011; Anonymous Expert 11, 2017). However, some say that if users are able to record work retrospectively, there is a risk that they simply forget to do so, and then the failure cannot be analysed (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017).	

Process Step	Definition	Justification	CMMS Implementation Spec.
2.03 [Optional] Attach Defect Tag	A hand-written tag is physically attached to the failed asset (Peters, 2014). The use of such tags is only recommended in certain contexts; arguments for and against are provided in the next column.	Comments in favour of using Defect Tags: • Tags provide a visual indication that the problem has already been reported, to prevent duplicate WO Requests (Anonymous Expert 2, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017); • Dated tags make it easier to see how long the problem has existed, to encourage a timely resolution (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017); • Tags are essential for safety reasons during maintenance execution. They provide a clear, visual indication of which asset the technician should be working on, to prevent accidental exposure to live equipment (Anonymous Expert 5, 2017; Anonymous Expert 6, 2017); • Tags are useful as a visual warning of a potential hazard (e.g. a leak) (Anonymous Expert 9, 2017). Comments against the use of Defect Tags: • Paper tags can suffer from perishability, particularly in outdoor environments (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017); • Tags can get left behind after the task is completed, leading to misinformation (Anonymous Expert 5, 2017); • Tags can be onerous to fill out, which discourages people from reporting defects (Anonymous Expert 7, 2017); • If a second defect occurs on the same asset, it may never get reported because there is already a tag present (Anonymous Expert 7, 2017); • Some CMMS packages can automatically inform the user if there is a duplicate WO Request (Anonymous Expert 8, 2017; Anonymous Expert 11, 2017); • In contexts where the asset is used by the general public / customers, "defect" tags would have a negative effect on customer perception and public relations (Anonymous Expert 10, 2017; Anonymous Expert 11, 2017); • Tags are not practicable in utilities / infrastructure contexts, where assets are spread over a huge geographical area (Anonymous Expert 11, 2017).	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
2.04 Create WO Request	Create a formal request for Emergent Work via the CMMS (Howard, 2004; Hickman, 2011; Ramskill, 2014; British Standards Institute, 2015b). The following mandatory fields are required (Monsanto, 2007; Peters, 2014; Ramskill, 2014; Shafeek, 2014; Duffuaa and Raouf, 2015): - Asset Record ID - Date, time - Problem description - Requester's name - Priority (suggested) - Asset Criticality - WO Request Type (the following types are recommended so that requests of a different nature can be managed via separate processes): o Corrective action request (i.e. in the event of a defect or breakdown) (Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017) o Modification / Change Request (i.e. step 1.01) (Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017) o WO Due Date Deferral Request (i.e. step 4.07) (Anonymous Expert 6, 2017). - **[Optional]** Cost Estimate. In contexts where maintenance execution is entirely outsourced, a cost estimate or quotation is required because cost is often the most significant factor in the approval decision (Anonymous Expert 10, 2017). - **[Optional]** Geospatial mapping data. Coordinates are entered to pinpoint the defect location; this functionality may only be applicable in contexts with large civil structures (e.g. a runway) or where assets are spread over a large geographical area (Anonymous Expert 10, 2017). Other information may be entered into the WO Request at this stage (depending on the knowledge of the requester); though these fields should not be mandatory: • Photo / attachment (Anonymous Expert 1, 2017) • Suggest materials requirements (Anonymous Expert 7, 2017) • Suggest access requirements (Anonymous Expert 7, 2017) • Suggest Work Team / Trade Skill requirements (Anonymous Expert 8, 2017) • Failure Codes (Fault / Damage / Cause / Remedy) (Anonymous Expert 8, 2017; Anonymous Expert 11, 2017)	Note that the Priority classification is only suggestive at this stage – the final decision is made by the screening group in step 2.14 (Institute of Nuclear Power Operations, 2010). It is important that the Criticality rating of the asset is clearly visible within any WO Requests or WOs raised against that asset. This information is essential during work prioritisation, to highlight the importance of the work and the potential consequences if it is not carried out on time (e.g. a breach of legal compliance or potential plant breakdown) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). Regarding who should create WO Requests, 2 options are presented – the correct choice depends on the context. Some sources suggest that requests should be handled via phone by an administrator / dispatcher, who then creates WO Requests on the requester's behalf (Kherun et al., 2002; British Standards Institute, 2004; Suttel, 2005; Peters, 2014). This reduces user training requirements and simplifies access control arrangements (Anonymous Expert 3, 2017; Anonymous Expert 4, 2017). A similar method involves filling out paper defect slips manually, which are then collected and entered into the CMMS by an administrator (Anonymous Expert 4, 2017). However, according to Kherun et al. (2002), this method can result in poor quality information if the call handler is not technically skilled (as is often the case). An alternative according to Peters (2014) and Duffuaa and Raouf (2015), is that everyone in the organisation should have the authority to raise their own WO Request – there is less room for misunderstanding if the request is made first-hand. This generally improves the quality of the information – i.e. the person who saw the failure first hand can often describe it best (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). However, this approach is not appropriate in contexts where requests are made by non-technical persons (e.g. members of the public, passengers, tenants etc.) (Anonymous Expert 10, 2017).	[WO Request, Field] Asset Record ID, Date, Time, Problem Description, Requester's Name, Priority, Asset Criticality, Photo / attachment, Materials Requirements, Access Requirements, Work Team, Failure Codes (Fault / Damage / Cause / Remedy) [WO Request, Field] WO Request Type = Breakdown, Defect, Change Request, or Due Date Deferral Request [WO Request, Function] Automatically record Date, Time, Requester's Name [WO Request, Field] Asset Criticality = (copied from Asset Record) [WO Request, Field] Geospatial coordinates [WO Request, Function] Geospatial mapping [WO Request, Function] Ability to restrict access for creating WO Requests to authorised persons

Process Step	Definition	Justification	CMMS Implementation Spec.
	[Optional] The WO Request is created via a mobile device that interfaces with the CMMS, rather than from a fixed computer terminal. This does not alter the content of this step, only the end-user experience. Additional CMMS functionality will be required to enable this optional feature.	This step is a good candidate for data entry via a mobile device in the field, which enables the technician to enter data without returning to the office. This reduces admin time and improves "Wrench time" efficiency (i.e. % of time spent per day actually doing maintenance). Some CMMS packages are available with mobile functionality (at an extra cost) (Anonymous Expert 11, 2017). Mobile devices are particularly useful in contexts in which assets are spread over a large geographical area, so that technicians can access the CMMS remotely to enter and retrieve data in a timely manner (Anonymous Expert 11, 2017).	[CMMS, Function] WO Request via mobile device, with suitable user interface
	A note on the relationship between WO Requests and WOs (not shown on flowchart because this is a one-off implementation consideration):	**[Optional] –** According to industry experts (see submission 6, section 3.2.3), in some contexts it is preferable to completely omit WO Requests from the MD Process. The alternative is to directly create a WO at step 2.04, with a "New Request" Status, and simply review this during the screening meeting. The advantage of this approach is that it is simpler to manage (i.e. there is only 1 CMMS "entity" instead of 2 for every task) – and simplicity increases the likelihood that the process will be followed willingly (Hickman, 2011; Anonymous Expert 12, 2017). However, this approach is only suitable in contexts where the CMMS package is able to provide a WO with all of the same fields and functionality that are available in a WO Request. In the author's experience, it usually does not – for example the following WO Request functionality is not available within a WO in SAP, a widely used CMMS package (Liebstuckel, 2012): • the ability to define request types (see step 2.04) • the ability to record failure codes (see step 5.40) • the ability to record detailed failure history and technician comments (see step 5.35) • the ability to assign multiple requests to a single WO (see step 2.17, Option B) Depending on the CMMS package in use, the functionality listed (and perhaps others) may or may not be available if WO Requests are omitted from the MD process. This framework will continue to be written with a WO Request entity present: if the option is selected to omit it, simply treat any mention of "WO Request" as a preliminary WO with the status = "New Request" (the MD process will remain the same in either case, i.e. all requests must be screened and approved before any work is authorised). However, please ensure that any desired WO Request functionality encountered in this framework is available within the WO of the CMMS package before continuing with this option.	
2.05 Default WO Request Status = "New Request"	New WO Requests have the default status "New Request".	So that new work can be easily identified during the screening process (Monsanto, 2007; Hickman, 2011; Ismail, 2014; Duffuaa and Raouf, 2015).	[WO Request, Status] New Request (default) [CMMS, Function] Search for and list out WO Requests by Status

Process Step	Definition	Justification	CMMS Implementation Spec.
2.06 [Optional] Pre-Screening Quality Check	If the Screening Process consists of a routine meeting with multiple stakeholders (i.e. Option A below), it may be appropriate to carry out a preliminary quality check on all new WO Requests prior to the screening meeting. This step is unnecessary if Options B or C are selected.	Most industry experts agree (see submission 6, section 3.2.3) that the following checks should be carried out for all new WO Requests prior to the screening meeting: • The Maintenance Team Leader / Supervisor should review all new WO Requests before the screening meeting to determine the full scope of work, investigate any information gaps, and delete any duplicates. The aim is to ensure that all required information is available during the screening meeting, so that a prompt decision can be made (Anonymous Expert 4, 2017; Anonymous Expert 9, 2017). • The Shift / Production Manager should sift through all new WO Requests and give a nominated priority prior to the screening meeting (to be discussed further and agreed at the meeting). The aim is to streamline the list to make the screening meeting more time-efficient (Anonymous Expert 2, 2017).	[WO Request, Status] New Request (default) [CMMS, Function] Search for and list out WO Requests by Status [WO Request, Field] Priority
2.07 Review outstanding requests	New WO Requests are screened to determine if they should be accepted, and then sent forward for planning and execution. With regards to the methodology used for the Screening Process, the following options are available: • **[Option A]** In a manufacturing environment, different departments (e.g. production, maintenance, safety) may have very different opinions as to which work should go ahead, and which is the highest priority; therefore most sources advocate a formal routine meeting (i.e. at least daily / shiftly) to allow all stakeholders to engage in the decision (Al-Turki et al., 2014; Peters, 2014; Duffuaa and Raouf, 2015). • **[Option B]** Alternatively, a single person can carry out the screening role provided that they are able to fairly balance the needs of all departments – i.e. if a dedicated production / maintenance coordinator role is in place (Monsanto, 2007; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017). • **[Option C]** Another option, which may be more suitable in a Facilities Management (FM) environment, is for a client / customer to screen all requests and make the decision directly (Kherun et al., 2002; Peters, 2014).	Multiple sources agree that WO Requests should pass through a screening process to ensure that only valid and meaningful work enters the MD process (Suttell, 2005; Institute of Nuclear Power Operations, 2010; US Department of the Army, 2013; Peters, 2014; Ramskill, 2014; Duffuaa and Raouf, 2015). Regarding option A, the following attendees are recommended for a Screening Meeting: - It is essential for Production and Maintenance Supervisors to be present, as they have a good working knowledge of the asset and its priorities (Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017). - Also include those who are ultimately responsible for asset performance (i.e. Production Manager / Maintenance Manager / Asset Manager), as they are key stakeholder(s) in any prioritisation decisions (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). - Health, safety and environmental representatives, and STO representatives can assist if applicable (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017). - It is useful to give technicians the opportunity to attend on occasion, in order to build awareness of the planning process (Anonymous Expert 7, 2017; Anonymous Expert 12, 2017). Screening meetings are best held little and often, to prevent the formation of an unmanageable stockpile of new requests. A quick, focused meeting every morning (approx. 10 – 15 minutes) should be sufficient to screen all new requests from the last 24 hours (Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). For larger sites, separate screening meetings can be held for each plant area, in order to reduce the request volume down to manageable levels (Anonymous Expert 8, 2017) In contexts were shift work is necessary, a screening frequency of "daily" may not be suitable – at the start of every shift may be more appropriate (Anonymous Expert 4, 2017).	[CMMS, Function] Search for and list out WO Requests by Status

Process Step	Definition	Justification	CMMS Implementation Spec.
2.08 Determine Scope	The full scope of the potential Emergent Work is determined so that a decision can be made as to whether or not it should be progressed (British Standards Institute, 2015b). If the scope is not clear, the screening team need to rectify this so that when the task moves forward to planning, there is a clear objective for the task. This information should be clearly recorded in the WO Description, and it should also be made certain that the correct Asset Record is selected in the WO, so that the work is recorded against the correct asset to enable performance monitoring and improvement (Baker, Booth and Wilson, 2013; Ismail, 2014; Shafeek, 2014).	This scope should be clear based on the information entered into the Problem Description field by the requester. The Pre-Screening Quality check in step 2.06 also ensures a clear scope description prior to screening. At this stage, it is also helpful if the screening team add any additional planning information that they can to the WO Request, to assist the planner during the next stage of the process: e.g. resource requirements, suitable execution methods, duration estimates. The attendees of the screening meeting are usually knowledgeable enough to offer some useful insight (but take care that this does not unnecessarily prolong the meeting) (Anonymous Expert 7, 2017).	[WO Request, Field] Problem Description
2.09 [Optional] WO Request Status = "Awaiting Information"	Most industry experts agree (see submission 6, section 3.2.3) that if it is not possible to determine the full scope of work during screening without further investigation, the WO Request should be added to a holding list using the status "Awaiting Information". Responsibility should be assigned to someone during the screening meeting to investigate and return with clarification.	It may not be possible to obtain a thorough scope of work from the requester – for example in an FM environment were the requester is not technically skilled (Kherun et al., 2002). Even in a manufacturing environment were requests are created by skilled technicians, the problem description can occasionally be unclear and require further investigation.	[WO Request, Status] Awaiting Information
2.10 Accept Request?	A decision to accept or reject the request is made based on the defined scope of work (Howard, 2004; Monsanto, 2007; Hickman, 2011; Ramskill, 2014).	Possible reasons for rejection include duplicate or vague requests (Monsanto, 2007; Peters, 2014; Ramskill, 2014), or if the cost of the work would outweigh the benefits (Kherun et al., 2002; Howard, 2004).	N/A
2.11 Confirm Rejection	If the request is rejected, then action must be taken in the CMMS to demonstrate this and remove it from the list of outstanding requests (Hickman, 2011; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017).	According to industry experts (see submission 6, section 3.2.3), there are two options available: - **[Option A]** Use a specific Status to flag the rejected work – e.g. "Rejected". This method removes the request from the list of outstanding work, but ensures that it can always be viewed for reference if necessary. - **[Option B]** Delete the WO Request. This will permanently remove it from the system, which is ideal for duplicates and other erroneous requests that are no longer needed.	[WO Request, Status] Rejected [WO Request, Function] Delete
2.12 Send feedback to requester automatically	Inform the person who requested the work that their proposal has been rejected, and explain why. When the rejection has been confirmed in the CMMS (either via a specific "Rejected" Status, or via deletion of the request, as per the options above in step 2.11) the CMMS should automatically request feedback via a pop-up window, which is then sent to the requester via email (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017).	Prompt feedback is essential for explaining why the request was rejected, in order to build respect for the emergent work process and to encourage users to continue to report defects with high quality information in the future. If requests are "ignored" then users will disengage with the process and begin to request work via other channels, which will undermine the MD process (Anonymous Expert 2, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017).	[WO Request, Field] Rejection Feedback [WO Request, Function] Rejection Feedback Field to become mandatory when Status = Rejected or WO Request Deleted (depending on option selected in step 2.11) [WO Request, Function] Email contents of Rejection Feedback Field to Requester when Status = Rejected or WO Request Deleted (depending on option selected in step 2.11)

Process Step	Definition	Justification	CMMS Implementation Spec.
2.13 Confirm Approval	If the request is approved, then action must be taken in the CMMS to demonstrate this and remove it from the list of outstanding requests (Monsanto, 2007; Duffuaa and Raouf, 2015).	According to industry experts (see submission 6, section 3.2.3), there are two options available: - **[Option A]** Use a specific WO Request Status to flag the approved work – e.g. "Approved". This method provides a clear indicator within the CMMS that the request has already been screened (i.e. by using the Status field). - **[Option B]** Do nothing. Shortly, in step 2.17, a WO will be created, linked to the WO Request. This will provide an alternative indicator within the CMMS that the request has already been screened (i.e. the "Associated WO" field within the WO Request will NOT be blank). Note however, that this means that step 2.17 must take place during screening, not after, as indicated on the flowchart (see step 2.17 for more details). These two options just provide subtly different ways of filtering out requests that have already been screened, so that they are not screened twice. It is just a matter of preference.	[WO Request, Status] Approved [WO Request, Field] Associated WO [WO Request, Function] Associated WO field automatically populated when a WO is created via a WO Request.

Process Step	Definition	Justification	CMMS Implementation Spec.
2.14 Agree Priority	An appropriate Priority classification is agreed for the work, which determines its Due Date (Suttell, 2005; Monsanto, 2007; Hickman, 2011; US Department of the Army, 2013; Al-Turki et al., 2014). The requester's initial Priority suggestion is taken into consideration and amended accordingly (Institute of Nuclear Power Operations, 2010).	Emergent Work must be ranked according to urgency, so that the most critical tasks are scheduled first (British Standards Institute, 2004; Sahoo, 2008; Modi, 2010; Ismail, 2014). Without clear priority definitions, complete with a range of corresponding due dates, it is difficult to address defects in a timely manner – which leads to long MTTR (Mean Time to Repair) scores and an increasing backlog of incomplete work (Anonymous Expert 3, 2017; Anonymous Expert 7, 2017; Anonymous Expert 10, 2017). Accurate and consistent prioritisation is vital for managing emergent work effectively with limited resources. The screening authority must question and scrutinise each request and ensure that the correct priority decisions are made, to avoid the development of an unmanageable backlog (see step 2.20) (Anonymous Expert 11, 2017). There are two commonly used methods for Emergent Work prioritisation: - **[Option A]** A linear Priority scale is used with approximately 5 levels (variable, depending on user preference) – the most appropriate priority is simply selected in each case based on the perceived urgency of the task (e.g. Immediate, Urgent, Normal, Minor) (Monsanto, 2007; Hickman, 2011; Institute of Nuclear Power Operations, 2010; Modi, 2010; Al-Turki et al., 2014; Ismail, 2014). - **[Option B]** A decision matrix or grid is utilised, typically with 2 axes depicting "impact of failure" and "time until failure", which are multiplied together to determine an appropriate Priority Score (Institute of Nuclear Power Operations, 2010; Fernandez and Marquez, 2012; US Department of the Army, 2013; Peters, 2014; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017). Option B is useful for ensuring consistent and objective priority decisions, which is helpful in contexts where there is an established culture of poor prioritisation decisions (i.e. "my problem is more important than yours") (Anonymous Expert 1, 2017; Anonymous Expert 4, 2017; Anonymous Expert 8, 2017). However, this method is more time consuming to use than Option A (i.e. 2 axes need to be considered and discussed as opposed to 1), and can therefore slow the screening process down; sensible priorities can be achieved using Option A if a small, experienced and consistent screening team make all of the decisions (e.g. Operations and Maintenance supervisor) (Peters, 2014; Anonymous Expert 6, 2017).	[WO Request, Field] Priority, Due Date [WO Request, Function] Due Date adjusted automatically based on Priority selection.

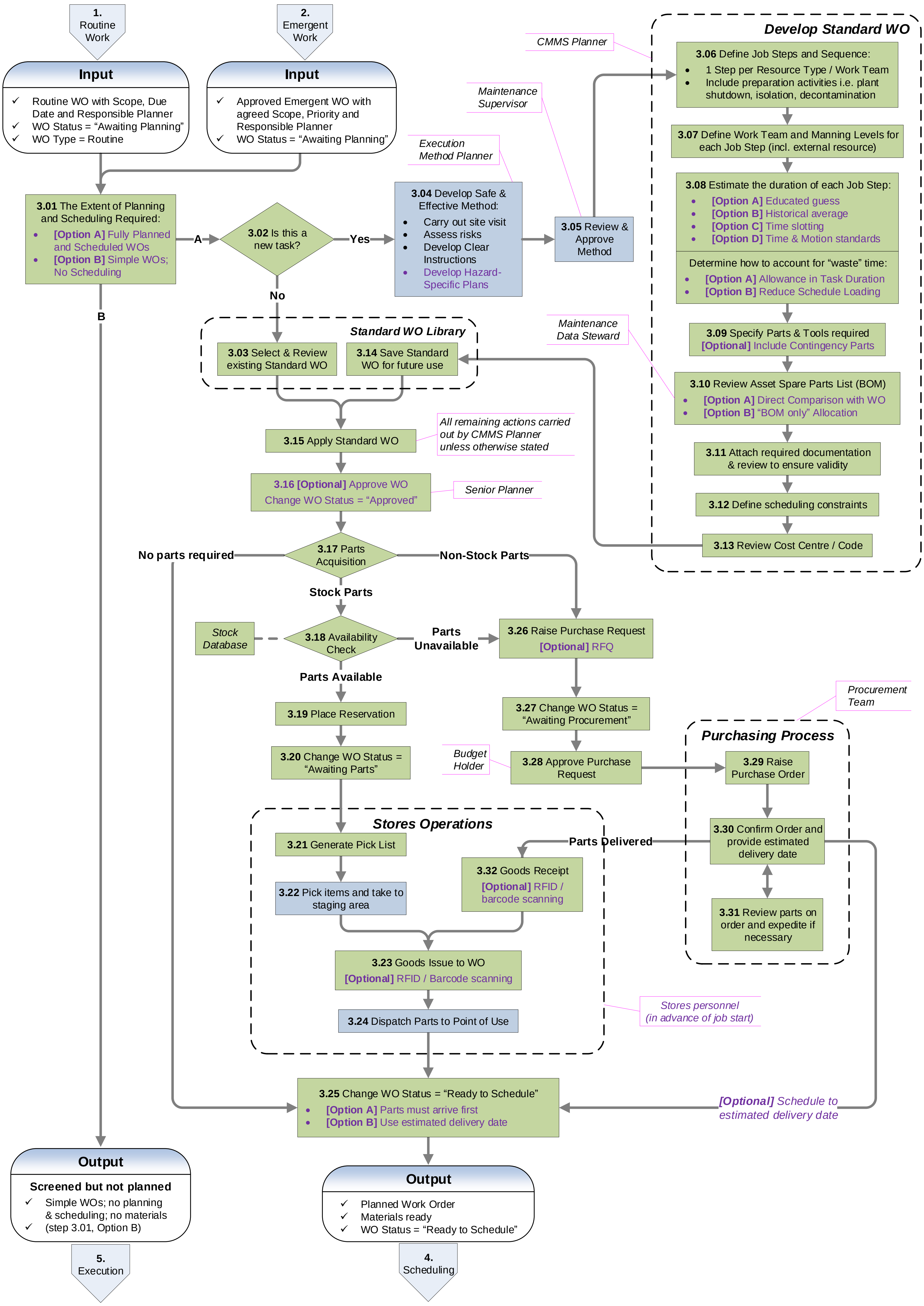
Process Step	Definition	Justification	CMMS Implementation Spec.
2.15 [Optional] Add Task to STO Holding List	If the task in question will require a STO (Shutdown / Turnaround / Outage) to enable execution, then it is allocated to the STO Holding List. Review of this list and assignment to a specific STO event is done at a later stage as part of a (separate) STO planning process (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017).	STO management takes place over a longer timescale, using a different business process which cannot be wholly incorporated into this one (which is designed for day-to-day maintenance). A STO planning process mixes in some project management principles, e.g. critical path and networking. The STO build-up and scope definition process is also different – tasks need to be planned much longer in advance (Anonymous Expert 12, 2017). For sites where STO maintenance takes place, it is essential to clearly identify any tasks that require a STO event, so that they can be grouped together into a STO work scope (Howard, 2004; Campbell and Reyes-Picknell, 2006; Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Hickman, 2011; Peters, 2014). Common methods for flagging STO work within the CMMS include utilising a specific Priority classification (Monsanto, 2007; Anonymous Expert 9, 2017) or Work Team (Anonymous Expert 8, 2017).	Create Priority Classification = STO Create Work Team = STO [WO Request, Field] Assigned STO Event
2.16 Assign Responsible Planner	An appropriate person is assigned responsibility for planning the WO (Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 12, 2017).	There are two different methods available: - **[Option A]** A named individual should be assigned to each task – this provides clear ownership and accountability to a single person, to ensure that the task will be progressed in a timely manner (Anonymous Expert 5, 2017). It also allows any follow up questions to the directed to the correct person more easily (Anonymous Expert 6, 2017). - **[Option B]** In some contexts, it is not always appropriate or possible to assign responsibility to an individual person (e.g. in contexts where planners work shifts) – in such cases it is acceptable to assign planning responsibility to a planning group or discipline-specific team instead (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017).	[WO Request, Field] Responsible Planner

Process Step	Definition	Justification	CMMS Implementation Spec.
2.17 Create Work Order	A WO is created for the approved task – now that the scope, priority and responsible planner have been agreed. This will enable the task to move forward into planning, scheduling and execution. The WO will be linked to the associated WO Request for reference, and will contain come of the same basic information – plus additional planning and cost details. Industry experts agree (see submission 6, section 3.2.3) that although this step is a key output of the Screening Process, the actual creation of the WO should take place afterwards, to save the time of the various stakeholders present. Once they have made a decision, it is acceptable to just set the WO Request status to "Approved", and let a planner create the WO outside of the screening meeting (however, this only applies if Option A is selected in step 2.13; Option B relies on a WO being created within the Screening Process to confirm the approval of the request).	An approved WO is the output of the screening process; it will be used to manage the task through the next stages of planning, scheduling and execution (Howard, 2004; Suttell, 2005; Institute of Nuclear Power Operations, 2010; Peters, 2014; Ramskill, 2014; Duffuaa and Raouf, 2015). There are 3 options available with respect to the relationship between WOs and WO Requests: - **[Option A]** A new WO is created for each and every approved WO Request. Each task has 1 WO Request representing the "problem" (e.g. defect, failure), and one corresponding WO representing and managing the "solution" (i.e. the work to be carried out to resolve the defect / failure). This provides a clear, direct link between the two entities (Anonymous Expert 11, 2017). - **[Option B]** Multiple WO Requests per WO, i.e. many requests (problems) are grouped together onto a single WO, to be resolved together. This is useful in contexts where assets are spread over a large geographical area, and a single person or team is assigned to execute multiple tasks which are taking place in a similar location at a similar time. The advantage is that the work is grouped together into a single package to simplify the assignment process and reduce the admin burden during WO closure. Individual WO Requests are still retained for each defect / failure in order to record and quantify them as separate "problems", but the cost and resource data for the overall "solution" is managed via a single WO (Anonymous Expert 11, 2017). - **[Option C]** Do not use WO Requests at all. As described earlier in step 2.04, there is an option to completely omit WO Requests from the MD process. In such cases, the WO Request information will already held within the WO – they are in effect a single entity, meaning that a direct 1-2-1 relationship is the only option. It is important that the Criticality rating of the asset is clearly visible within any WO Requests or WOs raised against that asset. This information is essential during work prioritisation, to highlight the importance of the work and the potential consequences if it is not carried out on time (e.g. a breach of legal compliance or potential plant breakdown) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).	[WO, Fields] Asset Record ID, Problem Description, Priority, Responsible Planner [WO, Function] Only permit creation if WO Request Status = Approved [WO, Field] Associated WO Request(s) [WO Request, Field] Asset Criticality = (copied from Asset Record)
	A note on WO numbering (not shown on flowchart because this is a one-off implementation consideration):	According to industry experts (see submission 6, section 3.2.3), there are two options available with respect to WO numbering formats: - **[Option A]** The WO is automatically assigned the next number in a sequence (within a defined number range). This method ensures that every WO has a unique ID number, which is essential. - **[Option B]** WO numbers are coded so that each character has a defined meaning, i.e. they conform to a specific pattern depending on certain characteristics (e.g. the first character represents WO Type, where 1 = Corrective Maintenance, 2 = Preventive Maintenance, etc.). This provides useful information about the WO at a glance, e.g. WO Type, location, discipline (Anonymous Expert 7, 2017).	[WO, Field] WO Number = sequentially generated within a defined number range [WO, Field] WO Number = coded according to pre-defined WO parameters.

Process Step	Definition	Justification	CMMS Implementation Spec.
2.18 [Optional] Define WO Type	It is common practice to categorise WOs based on the type of activity undertaken – using a "WO Type" field – so that these activities can be quantified and compared (e.g. to compare the cost or hours of reactive work in comparison to preventive work) (Anonymous Expert 1, 2017).	The following WO Type options are available; use any combination, depending on what needs to be measured and compared in the given context: - Corrective / Reactive Maintenance (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017) - Time Based / Preventive Maintenance (Anonymous Expert 8, 2017) - Condition Based Intervention / Predictive Maintenance (Anonymous Expert 1, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017) - Condition Assessment / Monitoring / Inspection (Anonymous Expert 9, 2017) - Project / Modification (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 9, 2017) - Root Cause Analysis (RCA) / Improvement time (Anonymous Expert 9, 2017) - Admin / Non-maintenance time (Anonymous Expert 9, 2017)	[WO, Field] WO Type = (Various, depending on user selection)
2.19 Default WO Status = "Awaiting Planning"	New WOs have the default status "Awaiting Planning".	So that planners can easily identify all newly approved WOs that require their attention (Hickman, 2011; Ismail, 2014; Duffuaa and Raouf, 2015).	[WO, Status] Awaiting Planning (default)
2.20 [Optional] Review Emergent Work Backlog	All Emergent Work that is approved but not yet executed is considered to be in "backlog" (Peters, 2014; Rødseth and Schjølberg, 2017; Shiver, 2017). Most industry experts agree (see submission 6, section 3.2.3) that it is important to periodically monitor the size and scope of this list, and to re-prioritise work if conditions change (note that it is possible to measure the backlog size in hours or in terms of the quantity of WOs).	The size of the Emergent Work Backlog is a critical measure of system control: If the quantity of outstanding work is increasing significantly over time (either in relation to number of tasks or number of man-hours of work), this shows that the MD process is failing – assets are accumulating defects at a faster rate than the system can respond to them (Anonymous Expert 1, 2017; Anonymous Expert 4, 2017). The cause could either be a lack of resources, the inefficient use of them (ultimately due to poor MD process design), or a failure to investigate and address the root causes of recurring defects (Jackson, 2016) – this will be discussed in section 6.	[CMMS, Function] Search for and list out WOs by Status [CMMS, Function] Sum total of listed WOs (by quantity or planned hours)
2.21 Notify Production Supervisor	On discovering a high priority failure, the requester promptly informs the Production Supervisor / Shift Manager by phone or PA system (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	If something has occurred which significantly impacts the plant or process, then the person responsible for that process must be made aware so that key decisions can be taken: 3. Confirm that the situation is indeed High Priority (Anonymous Expert 11, 2017) 4. Determine the best course of action to minimise the consequences	N/A
2.22 Notify Maintenance Supervisor	When aware of a high priority failure / breakdown, the Production Supervisor / Shift Manager promptly informs the appropriate Maintenance Supervisor by phone or PA system (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	Because they possess the expertise required to manage urgent / critical plant breakdowns in the most effective manner, and hence minimise the consequences. They are also well placed to assess the nature of the breakdown and judge who should be called upon to help form a plan of action.	N/A
2.23 Assemble Reactive Response team	Call an emergency meeting with the relevant experts, dependant on the nature of the breakdown (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	A diverse team with a broad range of skills will allow the most effective plan of action to be developed, i.e. representatives from Production, Maintenance, Planning, and SHEQ as appropriate.	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
2.24 Develop a plan of action	Determine the steps necessary to rectify the issue as quickly and safely as possible (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017).	A plan of action needs to be developed and implemented promptly to minimise the consequences of the breakdown.	N/A
2.25 High Priority Emergent Work Strategy	High Priority Emergent Work includes failures that need to be addressed more urgently (e.g. a critical asset failure resulting in a production stop or a safety / environmental / legal risk). There are two alternative approaches for the screening, planning and scheduling of such tasks: - **[Option A]** Screening, Planning and Scheduling is Fast-tracked - **[Option B]** Bypass Screening, Planning and Scheduling; Proceed directly to Execution Arguments for each option are presented in the next column.	- **[Option A]** No work should ever go ahead without a WO – no matter how urgent the task (Monsanto, 2007; US Department of the Army, 2013; Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017). This is the only way to ensure that every single task is properly screened and checked before going ahead and consuming limited labour resources, which need to be used wisely to address agreed priorities (Anonymous Expert 5, 2017; Anonymous Expert 11, 2017). If any work is allowed to bypass the screening process – even urgent or High Priority work – then it undermines the entire process because resources are not carrying out the work that was agreed, which ultimately results in poor maintenance performance (US Department of the Army, 2013; Shafeek, 2014). A WO also enables the task to be planned and scheduled effectively, and provides a record of work history (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017). However, High Priority tasks should not have to wait for the next screening meeting (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017); they can be "fast-tracked" through the screening and approval process (Suttell, 2005; Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Peters, 2014). The Production and Maintenance Supervisors will already be present and aware of the situation (from the previous 4 steps), and they have the authority to approve the WO Request immediately without waiting for the next screening meeting. The creation of the WO and the subsequent planning activities, can be carried out by a dedicated planner so that it does not "slow down" the execution effort (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017). These dedicated planners can also ensure that any potential opportunistic maintenance is included alongside the High Priority work (which will usually require an emergency plant shutdown) (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017). - **[Option B]** With High Priority work, resolving the problem as quickly as possible is more important than CMMS admin – in some contexts an immediate response is necessary because there is a fatality risk (e.g. power loss to a hospital); the WO can be created afterwards to save time (Hickman, 2011; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).	N/A

Framework Section 3 – Planning



Process Step	Definition	Justification	CMMS Implementation Spec.
3.01 Is planning and scheduling justified?	A decision must be made regarding the extent of planning and scheduling required for the task. There are two options: - **[Option A]** Fully planned and scheduled WOs. The task follows sections 3 and 4 in full. It is broken down into a sequence of discrete job steps, with estimated durations and manning levels for each. Parts and tools are specified and coordinated in advance. All activities are scheduled to optimise execution dates with available resources. - **[Option B]** Simple "one-liner" WOs, no scheduling. Sections 3 and 4 are skipped. WOs consist only of a simple, single-line description with a location and Due Date or Priority. Tasks are not optimised in a schedule, but simply listed in Priority / Due Date order and executed accordingly. Materials are withdrawn from the stores immediately prior to execution by the technician (where required). A note regarding WO Statuses: consider that the purpose of a WO Status is to show which stage of the planning and scheduling process the task is up to. If Option B is selected in this step, then the majority of planning and scheduling is skipped, therefore the WO does not need to use WO Statuses. Consequently the "Awaiting Planning" default status (currently assigned in step 2.19) need not apply. The "Responsible Planner" field as described in step 2.16 should also be replaced with a "Responsible Execution Supervisor / Coordinator".	Option A is recommended in more reactive / maintenance-intensive environments, with high workloads that place considerable pressure on a limited pool of labour resources (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). There is a clear negative effect on performance if planning and scheduling is neglected, and resources are consequently poorly coordinated and unable to deliver the required work, as shown by Samaranayake and Kiridena (2012) in their study of aircraft maintenance. Option B is appropriate in contexts where there is no value in detailed planning and scheduling, because resource availability is not the limitation (it may be another factor, such as cost) – for example if maintenance execution is entirely (or partially) outsourced with a flexible labour contract that can expand to meet peaks in demand (Anonymous Expert 10, 2017). For the same reason, option B is also commonplace in Facilities Management contexts (Kherun et al., 2002, Suttell, 2005). This decision may be universally applied to all work, or made on a task-by-task basis, depending on the context (Monsanto, 2007). For example, Option B could apply only to certain types of work, e.g. Emergent work which is very minor, or investigative work where the scope cannot be predetermined (and therefore cannot be planned in detail anyway) (Campbell and Reyes-Picknell, 2006; Institute of Nuclear Power Operations, 2010; Peters, 2014). According to the Institute of Nuclear Power Operations (2010), the decision can be made during screening (where competent people are present), and then communicated to the planner using the WO Type field. Note that if Option B is selected, planning is never completely "skipped", as some elements cannot be avoided (i.e. risks still need to be assessed, a safe method needs to be developed with clear written instructions, plant isolations must to be requested and coordinated, parts must be ordered / retrieved from the stores etc.). The result is that these planning activities are passed on to the technician, who will essentially have to plan their own work, immediately prior to execution (Kherun et al., 2002; Suttell, 2005; Ismail, 2014). This effectively slows down the execution of each task, and greatly reduces productivity or "Wrench Time" (i.e. the % of a technician's day spent actually doing maintenance) (Westerkamp, 1998; Peters, 2014; Shafeek, 2014). Fundamentally, technicians are skilled personnel employed to execute maintenance tasks, and as much of their time as possible should be dedicated to this – not spent at a computer writing method statements, or searching the stores looking for spares. A dedicated planner should do the planning, to facilitate the productivity of the technicians, and this is only possible with option A (Westerkamp, 1998; Peters, 2014; Shafeek, 2014; Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017).	[WO, Status] Awaiting Execution (default) [WO, Field] Responsible Execution Supervisor / Coordinator [WO, Field] WO Type = Detailed planning and Scheduling Required / Not Required

Process Step	Definition	Justification	CMMS Implementation Spec.
3.02 Is this a new task?	Determine whether the work is new, or if it has been done previously and was saved as a template in the "Standard WO" Library.	New tasks require planning from scratch, but if an existing Standard WO is used then this reduces planning time and ensures a consistent method for common activities (Rocheco, 2003; Howard, 2004; Peters, 2014).	[Standard WO, Fields] Standard WO ID, Standard WO Description [Standard WO, Function] Function as a WO template, containing all WO fields, with ability to store, retrieve and reuse
3.03 Select & Review existing Standard WO	Select a suitable existing Standard WO from the library. Review and check the validity of the content before use and amend as necessary.	It is good practice for the planner to review the existing task before use; it could contain out of date information, making the WO invalid or unsafe (Rocheco, 2003; Anonymous Expert 7, 2017).	[CMMS, Function] Ability to search for saved Standard WOs based on ID Number, Description

Process Step	Definition	Justification	CMMS Implementation Spec.
3.04 Develop Safe & Effective Method	A safe and effective method is developed for the new task: - Carry out a site visit - Assess any risks - Develop clear instructions The assessment not only considers safety risks, but also identifies any significant risks to the success of the task (e.g. spares availability, complex isolations, special tooling requirements, access requirements, weather conditions etc.), so that control measures can then be incorporated into the job method. The aim is to create the most effective plan possible, as well as the safest (British Standards Institute, 2004; Anonymous Expert 12, 2017). As well as defining how the work needs to be done, it is also important for the plan to explain why – i.e. what is the purpose of the task? What failure mode is this task addressing? This helps the technician to understand the importance of the work and provides a sense of ownership, which will improve work quality (Anonymous Expert 8, 2017). Note that for Emergent Work tasks, it is good practice to consult the requester of the work at this stage, in order to fully understand the problem and ensure that the execution method is suitable (Anonymous Expert 4, 2017). To develop a safe and effective method, the planner responsible must have sufficient technical capability and hands-on experience (i.e. usually an ex-technician) (Kherun et al., 2002; Suttell, 2005; Ismail, 2014). It is often difficult to recruit planners with both hands-on experience and the IT skills necessary to utilise the CMMS software (i.e. steps 3.06 onwards), therefore a common solution is to split the hands-on element of planning and the CMMS-based element into two different roles, that work together to plan each task (Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). An "Execution Method Planner" can be utilised to develop safe and effective methods – they will not execute tasks themselves, but utilise their experience to develop methods for others, including a site visit followed a detailed definition of the task scope, resource requirements, tooling requirements, access requirements etc. A "CMMS Planner" with the necessary software expertise can then be responsible for utilising this information to construct the WO, reserve / order parts and progress the job through to the scheduling phase (Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017).	A detailed Risk Assessment and Method Statement (RAMS) must be developed for every task – its purpose is to provide a safe and effective method / procedure with detailed instructions. This document is a regulatory requirement in many contexts, to ensure that safety risks are adequately controlled. The finished RAMS will require review and approval by a competent person prior to issue (Rocheco, 2003; Institute of Nuclear Power Operations, 2010; Peters, 2014; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 12, 2017). Peters (2014) describes a case from an oil refinery where vague task instructions contributed to poor maintenance performance. Instructions should be detailed enough for even a new technician to be able to understand what is required. This step is especially important if causal / semi-skilled contract labour is used (Anonymous Expert 12, 2017). If certain hazards are present, then additional, hazard-specific plans may be required: - **Isolation Plan** – If plant isolation is required prior to the commencement of the maintenance activity, then an isolation plan must also be developed (usually by the production department). This will detail exactly how the plant will be prepared, isolated, drained and cleaned etc. to ensure that every part of the maintenance task can be executed safely. This document will need to align closely with the method detailed in RAMS (see above) (Anonymous Expert 12, 2017). - **Lifting Plan** – If the task involves the use of lifting equipment (e.g. crane / hoist), then a separate lifting plan complete with a lifting risk assessment and method statement will be required for the lifting activity, to ensure that it is carried out safely. This is a legal requirement in certain countries (Anonymous Expert 12, 2017). - **Working at Height Plan** – If the task involves working at height (WAH) and requires the use of access equipment (e.g. scaffold / Mobile Elevated Work Platform), then an separate WAH plan complete with a WAH risk assessment and method statement will be required for the task, to ensure that it is carried out safely. This is a legal requirement in certain countries (Anonymous Expert 12, 2017).	N/A
3.05 Review & Approve Method	The task method is reviewed by a competent person to ensure that all risks have been assessed and that the method is suitable, safe and effective.	The finished RAMS will require review and approval by a competent person prior to issue; typically by a Maintenance Supervisor (Rocheco, 2003; Institute of Nuclear Power Operations, 2010; Peters, 2014; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 12, 2017).	

Process Step	Definition	Justification	CMMS Implementation Spec.
3.06 Define Job Steps and Sequence	Within the CMMS, the task is broken down into a sequence of independent Job Steps (Samaranayake and Kiridena, 2012; Ramskill, 2014; Shafeek, 2014; Duffuaa and Raouf, 2015): • Utilise 1 Step per Resource Type / Work Team • Include preparation activities i.e. plant shutdown, isolation, decontamination	Multiple steps are only necessary if multiple resource types are involved in the task – there should be one job step for each Work Team, so that they can be scheduled independently. For tasks that are executed by a single crew, then a single job step will be sufficient (Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). Preparation activities, often carried out by the Operations team, should be included in the list of Job Steps (Rocheco, 2003; Wulff, 2005; Campbell and Reyes-Picknell, 2006). These are often essential prerequisites, therefore it is useful during scheduling and execution to have full visibility of these activities and their completion status (Anonymous Expert 11, 2017).	[Standard WO, Field] Job Step (Sequentially numbered) [Standard WO, Field] Job Step Description [Standard WO, Field] Job Step Instructions
3.07 Define Work Team and Manning Levels for each Job Step	Specify which Resource Type / Work Team will be required to execute each Job Step (e.g. mechanical, electrical), and the number of technicians required. This should include external resources such as contractors.	Resource requirements are an essential part of maintenance planning (Keizers, Bertrand and Wessels, 2003; British Standards Institute, 2004; US Department of the Army, 2013; Shafeek, 2014; Duffuaa and Raouf, 2015). This information will be utilised during the scheduling phase to ensure that sufficient resources are allocated.	[Standard WO, Field] Job Step Work Team [Standard WO, Field] Job Step Manning Level

Process Step	Definition	Justification	CMMS Implementation Spec.
3.08 Estimate the duration of each Job Step	Various options exist for estimating task durations: • **[Option A]** Educated guess • **[Option B]** Time slotting • **[Option C]** Historical average • **[Option D]** Time & Motion standards	It is essential to estimate task durations for scheduling purposes (British Standards Institute, 2004; Lopez and Centeno, 2006; Sahoo, 2008; US Department of the Army, 2013; Shafeek, 2014). Various approaches were encountered in the literature; the best option will depend on the circumstances of the user: Educated guessing is a simple, low cost method, but it relies heavily on the experience of planners – if they are inexperienced, the schedule will ultimately be inaccurate, leading to delays and cancellations if insufficient time is allocated to tasks (Anonymous Expert 3, 2017; Anonymous Expert 9, 2017). It can also result in inconsistencies between different planners (Peters, 2014; Duffuaa and Raouf, 2015). Time slotting is a technique which aims to improve upon the inconsistencies of educated guessing, by allocating each task with a simple fixed time range (e.g. half day, full day). This technique is faster and recognises that estimating to a high level of detail is meaningless in most cases (Westerkamp, 1998; Campbell and Reyes-Picknell, 2006; Peters, 2014). This is particularly true for completely new tasks, where accurate estimates are not feasible and a "rough-cut" approach is more suitable (Anonymous Expert 6, 2017). The use of historical averages gives a more dependable estimation based on actual data, but this approach of course relies on the availability and accuracy of such data, which in most real cases is poor (Campbell and Reyes-Picknell, 2006; Lopez and Centeno, 2006; Peters, 2014). Some CMMS packages are able to automatically update task duration estimates based on historical average data (Anonymous Expert 2, 2017; Anonymous Expert 11, 2017), but without this functionality it is very time consuming to gather the data and make this calculation manually for every task (Anonymous Expert 7, 2017). Time standards derived via motion studies are accurate and extremely useful if made available, however they are time-consuming and expensive to produce, hence they are only feasible for highly repetitive tasks (Westerkamp, 1998; Al-Turki et al., 2014; Duffuaa and Raouf, 2015; Anonymous Expert 1, 2017; Anonymous Expert 5, 2017). In some contexts they are available from equipment manufacturers or from industry standards (Anonymous Expert 6, 2017). Note that in some industries, technicians can find Time & Motion studies demoralising or even insulting (Campbell and Reyes-Picknell, 2006) – therefore it is important that the reason is made clear to them – i.e. to improve the accuracy of job duration estimates, so that scheduling is more reliable (not for checking that people are working hard enough). It helps if technicians are audited by their peers, rather than by a supervisor or planner (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017).	[Standard WO, Field] Planned Duration, per Job Step and for the entire WO [Standard WO, Function] Automatically adjust Planned Duration based on historical averages

Process Step	Definition	Justification	CMMS Implementation Spec.
	Every activity will have an inherent amount of "waste" time, e.g. travelling to the job site, admin / paperwork, collecting tools / parts etc. The identification and elimination of this waste is a worthwhile goal, as it improves productivity / "Wrench Time", meaning that more work can be achieved with a given amount of resources (US Department of the Army, 2013; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017).	There are two approaches for allocating this waste: - **[Option A] –** Build an allowance into the task duration, i.e. increase the estimated duration of the task by a fixed percentage (approximately 10-20% is normally sufficient, depending on the context) (Campbell and Reyes-Picknell, 2006; Institute of Nuclear Power Operations, 2010; Peters, 2014). This approach accounts for the whole task, including any "waste", as a single entity. - **[Option B]** – Reduce the schedule loading (see next section, step 4.06), which effectively leaves gaps in the schedule to account for "waste" time (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017). This approach ensures that WO durations focus purely on the "useful" maintenance activity, and any waste is segregated out, which makes it easier to quantify (US Department of the Army, 2013; Anonymous Expert 7, 2017). If this option is selected, there is no need to add any contingency / allowance for waste at this stage – it will be added later during scheduling (see step 4.06).	[Scheduler, Function] Set Loading Restrictions
3.09 Specify Parts & Tools required	List all parts and tools required to carry out the task.	Materials requirements are an essential part of maintenance planning (Keizers, Bertrand and Wessels, 2003; British Standards Institute, 2004; Suttell, 2005; US Department of the Army, 2013; Ramskill, 2014; Shafeek, 2014; Van der Westhuizen and West, 2016). The aim is to ensure that all required parts, whether from stock or an external supplier, are available and ready to be used when the job starts. Defining exactly which parts are required is the first stage in this process. The inclusion of additional contingency parts is optional, depending on the context. Comments for: - Contingency parts are absolutely necessary when assets are spread over a large geographical area. If there is a 4 hour drive to the asset location, every possible part needs to be available in the back of the van, just in case (Anonymous Expert 11, 2017). Comments against: - In contexts where the majority of parts will not be used, consider that they will require booking back into stock again afterwards, which just creates unnecessary extra admin work (Anonymous Expert 6, 2017; Anonymous Expert 9, 2017). - In some cases this approach could lead to the re-ordering of materials that are not actually used, leading to unnecessary inventory (Institute of Nuclear Power Operations, 2010; Anonymous Expert 7, 2017). It is better to enable ad-hoc withdrawal of additional parts from the stores as and when required, so long as the goods issue process is efficient (Anonymous Expert 7, 2017).	[Standard WO, Field] Materials Required = (Stock Number, Description, Quantity) [Material Record, Field] Stock Number, Description, Stock Level [Material Record, Function] Return item to Stock [Standard WO, Function] Search Material Database

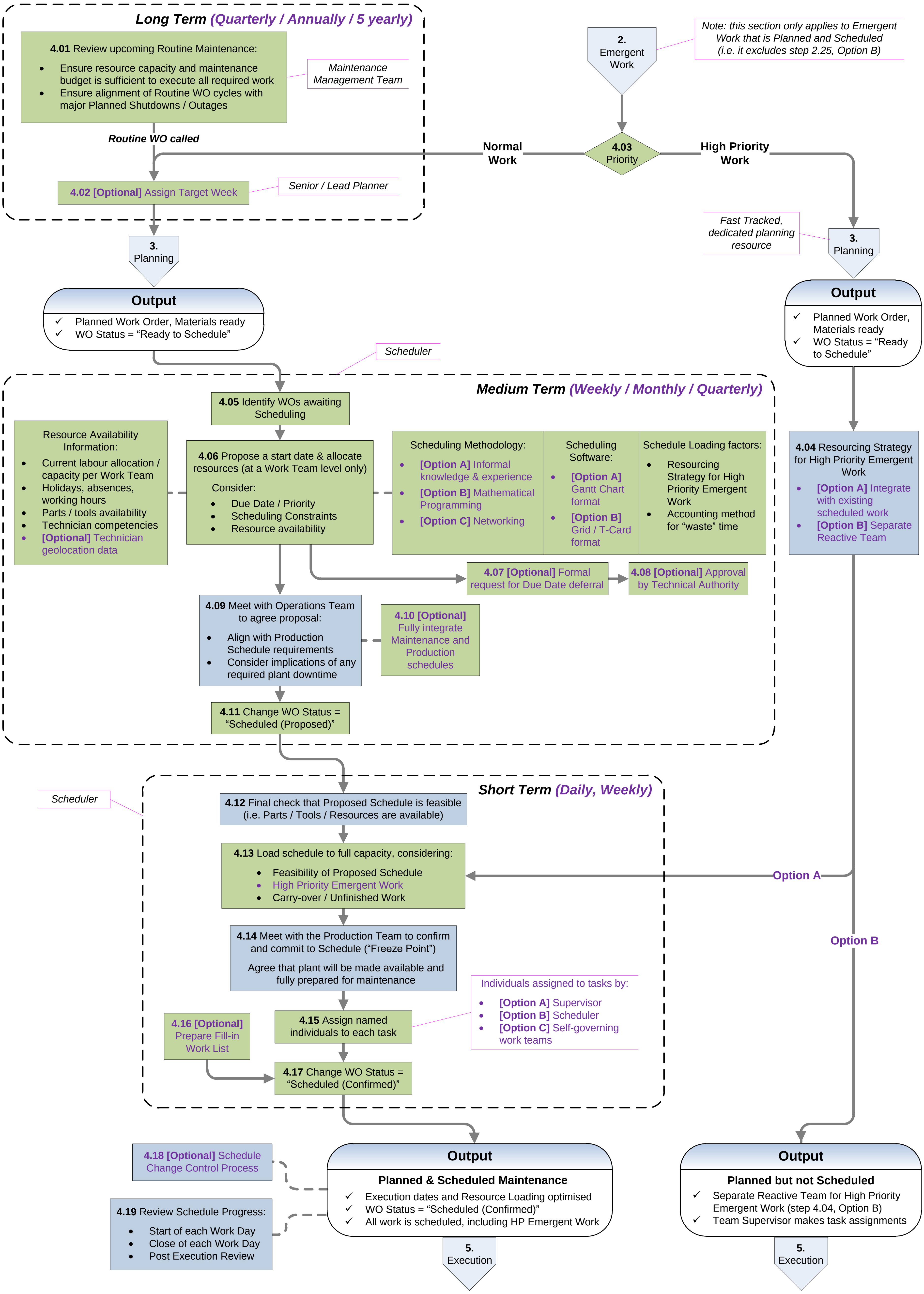
Process Step	Definition	Justification	CMMS Implementation Spec.
3.10 Review Asset Spare Parts List (BOM)	Check that any parts specified in the plan are consistent with those listed against the Asset Record (i.e. the BOM – see step 1.13) and adjust accordingly. Recall that the purpose of the BOM is to provide a list of critical or frequently used spares for each asset, which removes the need for planners to search the materials database manually when planning WOs, which saves time and reduces human error. Consider that BOMs are Asset Data, therefore authorisation to make changes should be tightly controlled and only possible for a small number of trained and competent people, in order to prevent malicious or accidental damage to data (i.e. "Maintenance Data Stewards" as per Section 1) (Anonymous Expert 7, 2017).	Asset Spare Parts Lists (BOMs) should be reviewed regularly to ensure that they are kept up to date – there is a good opportunity to do this during planning, to ensure that parts listed in the BOM are aligned to actual usage (Lachance, 2014). There are two methods available for doing this: - **[Option A]** Some CMMS packages include functionality that enables side-by-side comparison of WO material requirements with the asset's BOM. This makes it easy to see if materials are being used in a WO that are not listed in the BOM, so it can then be updated (Prometheus Group, 2016). - **[Option B]** The CMMS can be configured in such a way that it is only be possible to specify parts for a WO directly from the BOM (i.e. manual searching of the spares database is prohibited). If new parts are required, then they must be added to the BOM first – this effectively means that the BOM is always up to date, because planners are forced to update it if they want to use the parts in a WO (Anonymous Expert 2, 2017).	[Standard WO, Function] Compare Materials Required against Asset Record Spare Parts List (BOM), and allow adjustment if necessary (Prometheus Group, 2016) [Standard WO, Function] Material requirements can only be specified via the BOM; manual stock searches are prohibited.
3.11 Attach required documentation	Attach any documents that will be required during execution (e.g. safety procedures, drawings, manuals) (Shaw, 1998; Wulff, 2005; Shafeek, 2014; Duffuaa and Raouf, 2015).	Before attaching such items, it is necessary to review them to ensure that they are still valid and in date.	[Standard WO, Function] Attach documents
3.12 Define scheduling constraints	Define any constraints that should be considered by the scheduler during Section 4, e.g.: - Work can start any time (no constraint) - Work must fit in around production sequences / batches - Work requires a complete production stop / shutdown	This information is essential for the scheduler when they are proposing a start date – without this step, the scheduler must spend additional time searching for this information (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).	[Standard WO, Field] Scheduling Constraints = No Constraint, Production Sequence, Production Stop
3.13 Review Cost Centre / Code	Review where the costs for the work will be allocated (Cooper, 1998; Shaw, 1998; Duffuaa and Raouf, 2015).	So that maintenance expenditure can be categorised and analysed correctly. This information will already have been defined automatically in the Standard WO, based on the Cost Code assigned to the Asset Record (see step 1.10). However, in certain circumstances it may be necessary to change the default allocation, e.g. if the work is part of a project and needs to be assigned to a specific project cost code.	[Standard WO, Field] Cost Centre / Code [Standard WO, Function] Default Cost Centre / Code allocation to be based on that of the associated Asset Record
3.14 Save Standard WO for future use	Ensure that the completed Standard WO is saved as a template in the Standard WO Library.	So that it can be re-used in the future (i.e. step 3.03). New tasks require planning from scratch, but if an existing plan is re-used then this reduces planning time and ensures a consistent method for common activities (Rocheco, 2003; Howard, 2004; Peters, 2014).	[Standard WO, Function] Ability to store, search and retrieve [Standard WO, Fields] Standard WO ID, Standard WO Description
3.15 Apply Standard WO	The details of the Standard WO are applied to the WO, populating all relevant fields. If the task is a routine, then the Standard WO can also be applied to the Maintenance Plan (created in step 1.19) so that the Standard WO is used automatically for all subsequent WOs that are created by that plan (Wulff, 2005; Monsanto, 2007; Sahoo, 2008; British Standards Institute, 2009; Ismail, 2014).	New tasks require planning from scratch, but if an existing Standard WO is used then this reduces planning time and ensures a consistent method for common activities (Rocheco, 2003; Howard, 2004; Peters, 2014).	[WO, Function] Apply Standard WO details to WO [WO, Fields] Suitable fields to import all details from a Standard WO (see steps 4.04 – 4.11).
3.16 [Optional] Approve WO	The WO is reviewed and formally approved by a competent person (e.g. Senior Planner). This formal approval is indicated in the CMMS by changing the WO Status to "Approved".	To ensure that the WO fully aligns with the approved job method (i.e. step 3.05) and meets quality standards – this is a legal requirement in some contexts, particularly in high hazard industries (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 12, 2017).	[WO, Status] Approved

Process Step	Definition	Justification	CMMS Implementation Spec.
3.17 Parts Acquisition	In this section of the process, the parts specified in step 3.09 are retrieved from the stores and supplied to the point of use (note that although the term "parts" is used, this process also applies to tools and equipment (British Standards Institute, 2004; Barry, Olsen and Petit, 2011; Duffuaa and Raouf, 2015)).	As discussed in submission 4 (section 3.6.2), according to Van der Westhuizen and West (2016) this area of MM has the biggest impact on the MD process, and so is included in this framework. If there are no material requirements, then this section can be skipped as shown on the flowchart; e.g. in contexts where maintenance execution is entirely outsourced, with the provision of spare parts already included in the service contract (Anonymous Expert 10, 2017).	N/A
3.18 Availability Check	Check the existing stock levels for all materials specified in the WO.	To determine if enough stock is available or if materials need to be ordered (Shaw, 1998; Duffuaa et al., 2001; Barry, Olsen and Petit, 2011; US Department of the Army, 2013; Peters, 2014). This step is crucial for avoiding delays; stock data must be accurate – if stock levels are unknown or unreliable, then this often causes work to be cancelled or postponed (Anonymous Expert 3, 2017).	[WO, Function] Check stock levels of specified materials against required quantities
3.19 Place Reservation	If the required parts are available in stock, they are reserved against the WO (Shaw, 1998; Peters, 2014; Ramskill, 2014).	To prevent them from being accidentally used for a different task, to ensure that they are available during execution (Van der Westhuizen and West, 2016). In cases where two reservations are made for a single item of stock (i.e. it is "double-booked"), then the CMMS must be able to recognise this and bring it to attention of a planner so that a decision can be made (Anonymous Expert 7, 2017).	[WO, Function] Place Reservation for required materials [Material Record, Function] Restrict issue of reserved materials to the specified WO only [Material Record, Function] Highlight "double-booked" materials and request decision
3.20 Change WO Status = "Awaiting Parts"	The WO Status is changed to show that parts are reserved and are waiting for withdrawal from stock (Hickman, 2011; Ismail, 2014; Duffuaa and Raouf, 2015; Van der Westhuizen and West, 2016).	This status informs stores personnel that they are required to start the picking and dispatch process (Peters, 2014).	[WO, Status] Awaiting Parts
3.21 Generate Pick List	The CMMS generates a Pick List, which lists all parts requirements from the WO (Shaw, 1998; Barry, Olsen and Petit, 2011; Peters, 2014).	The list includes parts descriptions, quantities and locations to ensure that the correct items are withdrawn from stock.	[WO, Function] Generate Pick List
3.22 Pick items and take to staging area	Stores personnel remove the required stock from the shelves as specified by the WO pick list; parts are collected in a job-specific bin / tray and held in a staging area (Van der Westhuizen and West, 2016).	To gather all of the parts required for the job in one place.	N/A
3.23 Goods Issue to WO	Each item removed from the shelf is issued to the WO (Shaw, 1998; Peters, 2014; Ramskill, 2014; Duffuaa and Raouf, 2015).	To ensure that the cost of parts is correctly allocated to the maintenance task. **[Optional]** Barcode scanning or RFID (Radio-frequency Identification) functionality can be utilised to reduce the time taken for this step and to reduce data input errors (Teresko, 2003; Mele, 2007; Canaday, 2011; Lorenzi, 2017; Anonymous Expert 6, 2017).	[Material, Function] Goods Issue to WO [CMMS, Function] Data entry via RFID

Process Step	Definition	Justification	CMMS Implementation Spec.
3.24 Dispatch Parts to Point of Use	Stores personnel dispatch the job-specific bin / tray of parts to the job location in advance of the start date, so that the technician can begin working immediately on the day of execution without delay (Barry, Olsen and Petit, 2011; Van der Westhuizen and West, 2016).	This staging and dispatch approach greatly improves maintenance productivity, because technicians do not have to visit the stores at all – they just turn up at the work location and all parts and tools are ready and waiting, which frees up more of their time for doing useful maintenance work (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017). Additionally, if technicians collect their own parts there is a greater risk of stock withdrawals not being recorded, which reduces stock accuracy (which can lead to delays next time the part is required) (Anonymous Expert 1, 2017; Anonymous Expert 4, 2017). However, both options need to be possible: stores personnel should make all withdrawals for planned tasks, but technicians will still need access to the stores for unplanned, additional parts withdrawals (Anonymous Expert 7, 2017; Anonymous Expert 8, 2017) (this is covered later in step 5.14) or in circumstances where it is not practicable to dispatch to the point of use (e.g. with remote or unsecure job locations) (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017).	N/A
3.25 Change WO Status = "Ready to Schedule"	The WO Status is changed to inform the scheduler that planning is complete and that scheduling can take place (Monsanto, 2007; Hickman, 2011; Duffuaa and Raouf, 2015).	There are two options regarding when WOs should be marked "Ready to Schedule": - **[Option A]** Several sources argue that scheduling should not take place until parts have physically arrived and have been goods receipted (Duffuaa et al., 2001; Peters, 2014; Van der Westhuizen and West, 2016). - **[Option B]** However it is also possible to schedule work based on an estimated delivery date This option is riskier, because parts may arrive late and disrupt the schedule, but this approach can enable an earlier start time, and is often necessary for items with very long delivery times (Monsanto, 2007; Anonymous Expert 9, 2017).	[WO, Status] Ready to Schedule
3.26 Raise Purchase Request	If parts are not in stock, or if non-stock parts are required, then a Purchase Request (PR) is raised (Shaw, 1998; US Department of the Army, 2013; Ramskill, 2014). **[Optional]** In some circumstances (i.e. high cost purchases), it is necessary to send potential suppliers a Request for Quotation (RFQ) before raising a PR; a reliable estimate of cost may be required before approval can be granted (Anonymous Expert 7, 2017.	The PR will inform the procurement team that a purchase is required. All purchases need to follow the agreed procurement process to allow costs to be managed correctly (Bannister, 1996; Gay, 2005; Moldof, 2016). Some CMMS packages may be capable of automating this step to save time, i.e. if an availability check determines that the required parts are not available in stock (see step 3.18), then the CMMS should be capable of raising a Purchase Request (PR) automatically (Anonymous Expert 7, 2017).	[WO, Function] Raise PR for unavailable materials (manually) [WO, Function] Raise PR for unavailable materials (automatically) [PR, Fields] Material ID, Description, Quantity, Supplier, Due Date
3.27 Change WO Status = "Awaiting Procurement"	The WO Status is changed to "Awaiting Procurement".	This WO Status clearly highlights any jobs that cannot proceed until additional materials have been purchased, accountability is given to the procurement team to progress in a timely manner (Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017).	[WO, Status] Awaiting Procurement
3.28 Approve Purchase Request	The PR is approved by the relevant budget holder (Gay, 2005; Ramskill, 2014; Moldof, 2016).	To ensure that costs are controlled effectively; however, budget holders commonly allow purchases below a certain value to be self-approved by planners or technicians, in order to speed up the procurement process (Barry, Olsen and Petit, 2011; Peters, 2014; Shafeek, 2014; Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017).	[PR, Status] Approved [PR, Function] Approval by budget holder

Process Step	Definition	Justification	CMMS Implementation Spec.
3.29 Raise Purchase Order	A Purchase Order (PO) is raised once the PR is approved (Shaw, 1998; Lachance, 2012; Ramskill, 2014; Moldof, 2016).	A PO allows the procurement team to clearly and explicitly communicate the required purchase to a supplier (Van der Westhuizen and West, 2016).	[PO, Function] Prevent creation without an approved PR
3.30 Confirm Order and Estimated Delivery Date	The procurement team provides confirmation to the planner that the order has been placed (Cooper, 1998; Barry, Olsen and Petit, 2011) and provides an estimated delivery date (Anonymous Expert 7, 2017; Anonymous Expert 12, 2017).	To show that action has been taken by the procurement team and that delivery has been arranged. Once a delivery date is known and has been confirmed in the PO, the CMMS should be capable of automatically updating the Material Record with the latest lead time information.	[PO, Status] Order Placed [PO, Field] Estimated Delivery Date [Material Record, Field] Estimated Delivery Time [Material Record, Function] Automatically update Estimated Delivery Time based on historical PO delivery time
3.31 Review parts on order and expedite if necessary	Review all parts on order, check if any delivery dates have not been met, and expedite orders if necessary (Institute of Nuclear Power Operations, 2010). It is good practice to hold a formal routine meeting in which to carry out this review, involving key stakeholders from maintenance planning, warehouse management and procurement (Anonymous Expert 7, 2017).	To ensure that suppliers fulfil their obligations and do not cause delays. To effectively track outstanding orders, the CMMS should provide clear visibility of all parts on order with their respective WO, PR, PO numbers, supplier contact details and estimated delivery dates (Anonymous Expert 7, 2017; Anonymous Expert 12, 2017). It should also clearly highlight any late deliveries (Prometheus Group, 2016).	[CMMS, Function] Provide visibility of outstanding POs and highlight where delivery dates are passed without a goods receipt (Prometheus Group, 2016)
3.32 Goods Receipt	Delivered items are received into the stores, contents are checked against the delivery note, and the CMMS is updated to confirm receipt (Shaw, 1998; Barry, Olsen and Petit, 2011; Ramskill, 2014; Van der Westhuizen and West, 2016).	To show that all parts have arrived correctly and the supplier can be paid. **[Optional]** Barcode scanning or RFID (Radio-frequency Identification) functionality can be utilised to reduce the time taken for this step and to reduce data input errors (Teresko, 2003; Mele, 2007; Canaday, 2011; Lorenzi, 2017; Anonymous Expert 6, 2017).	[PO, Function] Goods Receipt [CMMS, Function] Data entry via RFID

Framework Section 4 – Scheduling



Process Step	Definition	Justification	CMMS Implementation Spec.
4.01 Review upcoming Routine Maintenance	The maintenance management team review all Routine WOs that will be generated over the long term to: - ensure that resource capacity and maintenance budget are sufficient to execute all required work (Keizers, Bertrand and Wessels, 2003; Baker, Booth and Wilson, 2013; Peters, 2014) - schedule major STO events in alignment with other routine maintenance requirements (Institute of Nuclear Power Operations, 2010; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). - schedule major STO events in alignment with other sites in the region, if local contractor availability is limited (Anonymous Expert 12, 2017). - ensure that tasks with seasonal restrictions are scheduled at the correct time of year (Anonymous Expert 10, 2017).	Several sources divide the scheduling process into 3 stages, but the timescale for these stages can vary depending on the context: Short Term (ST) ranges from daily to weekly, Medium Term (MT) ranges from weekly to monthly to quarterly, and Long Term (LT) ranges from 3 monthly to 5 yearly (Canaday, 2008; Al-Turki et al., 2014; Duffuaa and Raouf, 2015). Exact timescale definitions will depend on the requirements of the user and how far ahead they prefer to schedule work. It is good practice to make the long term schedule visible to all team members (e.g. publish on a notice board), so that everyone is aware of any upcoming events that may disrupt normal activities (Anonymous Expert 4, 2017).	[Graphical Scheduler, Function] View and adjust Maintenance Plans that will be generated in the future (Prometheus Group, 2016)
4.02 [Optional] Assign Target Week	For each Routine WO generated, a target week within the execution window is assigned by the senior / lead planner to provide a clear planning deadline; this process can also apply to any Normal Priority Emergent Work (Institute of Nuclear Power Operations, 2010).	In contexts where execution windows are large, the refinement of target dates can provide greater clarity for planners. It is also easier to manage high volumes of tasks through the scheduling process when they are grouped together into discrete, week-long packages. This allows them to be planned, resource loaded and reviewed together as a block, with a single person made responsible for each work week (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017).	[WO, Field] Target Execution Week
4.03 Emergent Work Priority	Note that this section only considers Emergent Work that is planned and scheduled; if Option B is selected in step 2.25, then High Priority Emergent Work will have already skipped directly to execution (see section 5).	Emergent Work is planned and scheduled differently depending on its Priority classification (Campbell and Reyes-Picknell, 2006; Sahoo, 2008). The normal route is for Emergent Work to be scheduled in the same way as Routine work. However, High Priority Emergent Work is managed differently due to the greater level of urgency (e.g. a critical asset failure resulting in a production stop or a safety / environmental / legal risk). If Option A is selected in step 2.25, then the screening, planning and scheduling of High Priority Emergent Work is “Fast-Tracked” (Suttell, 2005; Institute of Nuclear Power Operations, 2010; Peters, 2014) with dedicated planning resource assigned to address the urgent breakdown in a timely manner (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017).	[WO, Field] Priority [WO, Field] WO Type = Emergent

Process Step	Definition	Justification	CMMS Implementation Spec.
4.04 Resourcing Strategy for High Priority Emergent Work	There are two possible approaches for resourcing High Priority Emergent Work: • **[Option A]** High Priority Emergent Work is scheduled alongside Routine work, and shares the same pool of labour resource. Leave a percentage of the MT schedule free to allow slack for any High Priority Emergent Work that arises during the ST period (Keizers, Bertrand and Wessels, 2003; Campbell and Reyes-Picknell, 2006; Monsanto, 2007; Duffuaa and Raouf, 2015). • **[Option B]** Do not schedule High Priority Emergent Work. Load the MT schedule to 100% with routine work, and utilise a separate team to address High Priority Emergent Work as it arises (Institute of Nuclear Power Operations, 2010; Hickman, 2011). The choice will require careful consideration by the user based on their context and resourcing strategy.	With Option A, the level of schedule slack should match the anticipated level of Reactive work (Anonymous Expert 3, 2017; Anonymous Expert 5, 2017). This can vary hugely between contexts: some authors suggest 10-20% (Keizers, Bertrand and Wessels, 2003; Campbell and Reyes-Picknell, 2006; Duffuaa and Raouf, 2015), whilst in highly reactive environments 50% or even greater can be required (Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Shiver, 2017). Insufficient slack leads to increased overtime costs, delays and cancellations – which can damage stakeholders' trust. In contexts with high reliability and consequently very low levels of reactive work, loading the schedule to 100% is possible – any emergent work can be accommodated by postponing low priority "sacrificial" work, or by using overtime as a last resort (a clear decision process needs to be in place for controlling this however – i.e. step 5.17) (Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). Option B can enable a faster response in emergency situations and is designed to protect other scheduled work from being displaced (Institute of Nuclear Power Operations, 2010). This avoids the need to sacrifice any routine work in the event of a breakdown, enabling scheduled work to be 100% predictable, many weeks in advance (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017). This is a useful remedy in highly reactive environments with unpredictable levels of emergent work; scheduled work will be protected from knee-jerk cancellation in the event of a breakdown (Anonymous Expert 7, 2017). However, because the volume of High Priority work is unpredictable, there is a greater risk of poor resource utilisation because the Reactive Team must be manned for the worst case (Peters, 2014; Duffuaa and Raouf, 2015; Anonymous Expert 6, 2017). It could also be argued that having a special "reactive" team sends the wrong message – essentially condoning reactive work, which is more expensive and carries greater safety risks (Anonymous Expert 3, 2017). Note that with this option, the assignment of individuals to specific tasks will be managed by the Reactive Team Supervisor (Institute of Nuclear Power Operations, 2010; Hickman, 2011).	N/A
4.05 Identify WOs awaiting Scheduling	During MT scheduling, the Scheduler identifies all Routine and Normal Priority Emergent WOs which are fully planned and hence are ready for scheduling (see step 3.25) (Al-Turki et al., 2014; Peters, 2014; Duffuaa and Raouf, 2015; Shiver, 2017).	Work cannot be scheduled until it has been planned and all resources requirements are specified. The appropriate timescale for medium term scheduling depends on the context. Consider the following: • How long does it take to plan and prepare for a typical maintenance task (Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017)? • How much flexibility is desired for rescheduling if something goes wrong (Anonymous Expert 2, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017)? • What is the typical lead time for parts? For older assets where spares often have to be fabricated from scratch, a medium term range of up to 30 weeks can be considered normal (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017).	[WO, Status] Ready to Schedule

Process Step	Definition	Justification	CMMS Implementation Spec.
4.06 Propose a start date & allocate resources	The Scheduler proposes a start date for each WO and allocates resources, considering: • The WO Due Date (for Routine Work) or Priority classification (for Emergent Work) (British Standards Institute, 2004; Al-Turki et al., 2014; Peters, 2014; Duffuaa and Raouf, 2015). Proposed start dates can be allocated anywhere within the execution window (i.e. between the Earliest Possible Start Date and the Due Date) (Keizers, Bertrand and Wessels, 2003; US Department of the Army, 2013; Ismail, 2014). • Any Scheduling Constraints specified during planning (see step 3.12) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). • The availability of any resources required for the task (i.e. labour, parts, tools) (Duffuaa et al., 2001; British Standards Institute, 2009; Duffuaa and Raouf, 2015) (more details below – see Scheduling Software). Discussed below are 3 strategic, one-off decisions that also influence this stage of the scheduling process, i.e. scheduling methodology, software and loading strategy.	For MT scheduling, resource allocation takes place only at a Work Team level; specific individuals are not assigned to tasks until the ST section of the process (Westerkamp, 1998; Campbell and Reyes-Picknell, 2006; Peters, 2014) – see step 5.14.	[WO, Field] Scheduled Start Date, Scheduled Finish Date, per Job Step [WO, Field] Job Step Work Team [WO, Field] Scheduling Constraints
(4.06) Scheduling Methodology	The methodology for scheduling must be determined first. 3 principal scheduling methods were encountered in the literature: • **[Option A]** Informal knowledge & experience • **[Option B]** Mathematical Programming • **[Option C]** Networking However, according to industry experts, scheduling manually using informal knowledge and experience is the only realistic option in practice; i.e. a careful balancing of task due dates with resource availability, using experienced judgement (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). The other options are only included here to provide a comprehensive review of all options.	Option A relies on the scheduler's knowledge and experience; a judgement is made regarding appropriate start dates, by balancing workload with resource availability. This approach is the simplest and often produces good results in practice, provided that a suitably skilled scheduler is available (Keizers, Bertrand and Wessels, 2003; Samaranayake and Kiridena, 2012; Al-Turki et al., 2014). Mathematical programming techniques utilise software algorithms, which are useful for optimising large-scale, complex scheduling problems – for example when scheduling production and maintenance tasks together (Raza and Al-Turki, 2007; Berrichi et al., 2009; Kellerer, Rustogi and Strusevich, 2013; US Department of the Army, 2013; Kumar and Lad, 2017). However, they require large amounts of reliable data (which is generally not available) and are too complicated and impractical for real-life maintenance cases (Al-Turki et al., 2014). Networking techniques are commonly used when scheduling projects, to visually show the relationships between the various stages of complex tasks, estimate the duration of each stage, and determine the critical path (Campbell and Reyes-Picknell, 2006; Samaranayake and Kiridena, 2012; Al-Turki et al., 2014). These techniques are considered to be too detailed for the majority of day-to-day maintenance tasks, but may be useful for scheduling STO activities, which are comparable to large projects (Al-Turki et al., 2014).	

Process Step	Definition	Justification	CMMS Implementation Spec.
(4.06) Scheduling Software	In order to schedule manually using informal knowledge and experience, it is essential to utilise dedicated maintenance scheduling software, enabling tasks to be visually displayed and optimised in alignment with resource availability, by trial and error (Campbell and Reyes-Picknell, 2006; Barry et al., 2011; Al-Turki et al., 2014; Peters, 2014; Duffuaa and Raouf, 2015; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). Scheduling software is generally available in two alternative formats: • **[Option A]** Gantt Chart format • **[Option B]** Grid / T-Card format Whichever option is selected, the software must also be capable of supplying resource availability data to be effective; again, in an easy to use, visual format (Campbell and Reyes-Picknell, 2006; Al-Turki et al., 2014; Shafeek, 2014). This should include: • current labour allocation and total capacity for each period (e.g. per day), per Work Team and per individual (Sahoo, 2008; British Standards Institute, 2009; Al-Turki et al., 2014; Shiver, 2017). • holidays, absences, working hours (Campbell and Reyes-Picknell, 2006; Institute of Nuclear Power Operations, 2010; Peters, 2014). • parts / tools availability (Duffuaa et al., 2001; British Standards Institute, 2009; Duffuaa and Raouf, 2015). • technician competencies, which can help the scheduler to allocate tasks to the right person who is suitably trained, skilled and authorised to carry out the task (Cooper, 1998; Anonymous Expert 11, 2017). • **[Optional]** geolocations of technicians, utilising a GPS signal from the technician's mobile device (Anonymous Expert 11, 2017; Lorenzi, 2017). This is only applicable in a utilities / infrastructure context where assets and resources are spread over a large geographical area. In such cases the real-time positioning of each technician is important for optimising routes, reducing travel times, and getting someone to the task quickly in an emergency.	A Gantt Chart format allows for a highly detailed schedule, with a clear, visual indication of start and finish times for each activity; relationships can also be established between tasks (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). This is essential for STO events, where more precise timings are necessary in order to achieve a very accurate schedule and minimise the length of the production outage (Anonymous Expert 12, 2017). By contrast, with a Grid or T-Card format all WOs occupy a single, uniform time slot, so there is no visual indication of task duration, nor relationships between tasks (Anonymous Expert 5, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). This method is typically only able to schedule to the nearest day or half-day, but it is very simple to use and understand, which makes it a valid choice in certain contexts. In manufacturing plants for example, the precise execution start time needs to remain fairly flexible anyway in response to plant conditions (Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). Curiously, many CMMS packages do not have suitable scheduling functionality available as standard, which causes significant problems for many industry users (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). Companies typically purchase a separate software programme for scheduling or develop their own using spreadsheet software (which is not recommended – such solutions are very time consuming to update and prone to human error), but the consequence of the scheduler being external to the CMMS is that WO data and resource data have to be transferred back and forth on a batch basis (either manually or via a routine upload). This can be a time-consuming process that also results in multiple versions of the same data that are not completely in alignment. This problem can only be eliminated by utilising a CMMS package that has an integrated scheduling tool.	[Scheduler, Function] View and adjust WO scheduled dates and resource allocations (Prometheus Group, 2016; SAP, 2016) [Scheduler, Function] Display current labour allocation and total capacity for each period, per Work Team and per individual [Scheduler, Function] Display holidays, absences, working hours per individual [Scheduler, Function] Display relevant parts / tools availability [Scheduler, Function] Display / resource competencies [Scheduler, Function] Provide technician geolocation data

Process Step	Definition	Justification	CMMS Implementation Spec.
(4.06) Schedule Loading Strategy	Schedule loading is the total amount of work scheduled, compared to the total hours of labour available (expressed as a percentage) (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017). The target for schedule loading depends on: - The Resourcing Strategy for High Priority Emergent Work (see step 4.04) - The chosen method for accounting for "waste" time within each task (see step 3.08).	If Option A is selected in step 4.04, then schedule loading should be reduced in line with the expected volume of reactive work (e.g. to 80%), in order to leave sufficient resource unallocated (or on low priority sacrificial work) for in the event of a breakdown. If Option B is selected, then loading can remain at 100%. If Option B is selected in step 3.08, then schedule loading should be reduced further to account for the "waste" time inherent in each task (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017). This approach ensures that WO durations focus purely on the "useful" maintenance activity, and any waste is segregated out, which makes it easier to quantify (Anonymous Expert 7, 2017). If Option A is selected, then schedule loading need not be reduced (as the "waste" is already accounted for within each WO duration). Consider that it is also possible to deliberately overload the schedule (e.g. to 120%) – this is risky as it could apply excessive pressure to work teams, but in some cases this is an effective way to improve productivity (Anonymous Expert 11, 2017). It is worthwhile experimenting with loading levels to find the optimum point for a given context.	[Scheduler, Function] Set Schedule Loading limits and warning periods, with visual indicators when reached
4.07 [Optional] Formal request for Due Date deferral	If it is not possible to schedule a WO before its Due Date, then the Scheduler has to make a formal request for an extension (US Department of the Army, 2013).	According to industry experts (see submission 6, section 3.2.5) in some contexts this step is only required for safety-critical or regulatory work; but in other contexts it is considered good practice for all types of work. The formal request should be made via a specific WO Request Type in the CMMS, to enable the deferral process to be managed and recorded for control and auditing purposes (Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017).	[WO Request, Field] Type = Deferral Request [WO, Field] Scheduled Start Date, Scheduled Finish Date [WO, Function] Prevent Scheduled Finish Date > Due Date without approval
4.08 [Optional] Approval by Technical Authority	The deferral request is considered by a technical authority (e.g. responsible engineer or asset manager); they must assess the risk associated with not completing the work on time before an extension can be justified (Institute of Nuclear Power Operations, 2010; US Department of the Army, 2013; Anonymous Expert 6, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017).	The risks of not carrying out the work on time must be considered. If the risk is deemed to be acceptable, then the extension can be granted, and the WO can be scheduled beyond its Due Date. If the risk is too great, then the request is rejected and production will have to shut down until the work can be completed. This decision can be recorded within the Deferral WO Request (i.e. set the Status to Approved or Rejected, as with the Emergent Work process in section 2), in order to provide a robust audit trail (Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017).	[WO Request, Status] Approved [WO Request, Status] Rejected
4.09 Meet with Production Team to agree proposal	The scheduler holds a routine coordination meeting with the Production Team to agree the proposed schedule: • Ensure alignment with Production Schedule requirements (Institute of Nuclear Power Operations, 2010; Peters, 2014; Shafeek, 2014; British Standards Institute, 2015a). • Consider the implications of any required plant downtime (Campbell and Reyes-Picknell, 2006; Baker, Booth and Wilson, 2013; Duffuaa and Raouf, 2015).	Agreement must be reached with this key stakeholder to ensure that the work scope is supported and performed in accordance with the schedule (Hickman, 2011; Institute of Nuclear Power Operations, 2010).	N/A

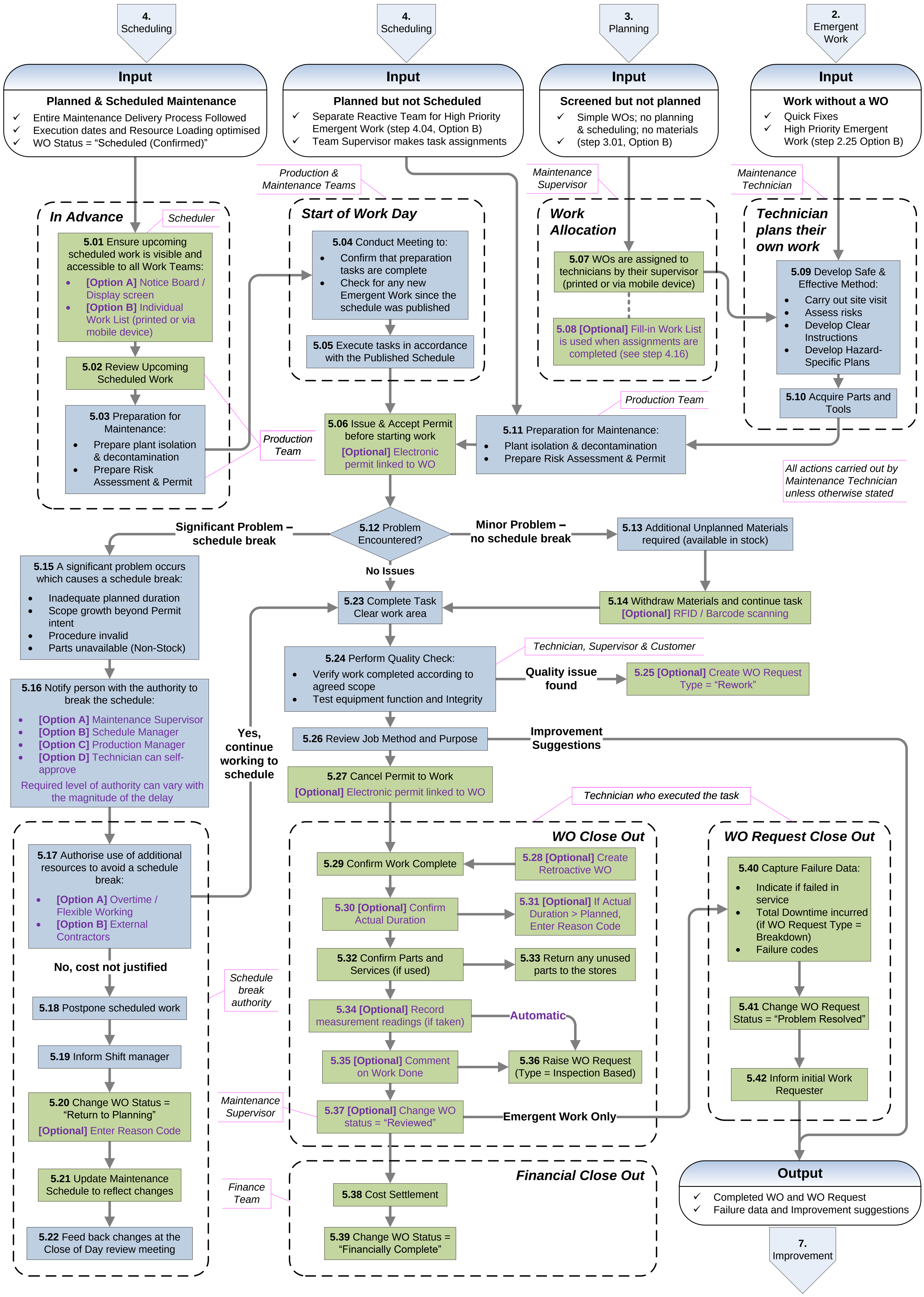
Process Step	Definition	Justification	CMMS Implementation Spec.
4.10 [Optional] Fully integrate Maintenance and Production schedules	Combine the scheduling of maintenance and production activities together into a single process.	Production and maintenance activities are traditionally scheduled separately, but there is a case for integration considering that they have aligned objectives (e.g. plant reliability, production output), and that they are inter-dependant (i.e. some maintenance tasks require a production outage) (Cooper, 1998; Al-Turki et al., 2014; Peters, 2014; Kumar and Lad, 2017). Integration of the maintenance and production schedules would be most beneficial in a batch or multi-product manufacturing context, to provide visibility of when certain machines are offline and hence are available for maintenance. Such integration would be less useful in a 24/7 operating context with a steady production output – if the plant is always online, then the production schedule would not provide any useful information for maintenance. However, even plants that operate "24/7" have their offline periods (i.e. STO events) – so in this context it makes more sense to show planned plant outages, rather than planned production periods, on the maintenance schedule to improve visibility (these could be blocked out with provisional dates as part of the long-term scheduling phase – i.e. step 4.01) (Anonymous Expert 7, 2017). Another way to improve the coordination of the production and maintenance schedules is to establish a single role with the responsibility for scheduling both work streams (i.e. an Integrated Schedule Manager / Coordinator) (Anonymous Expert 4, 2017; Anonymous Expert 9, 2017).	[Scheduler, Function] Enable the scheduling of both maintenance and production activities together (Prometheus Group, 2016)
4.11 Change WO Status = "Scheduled (Proposed)"	The Status is changed to show that MT scheduling is complete: the WO has been allocated a proposed start date, and this has been agreed with the Operations Team.	This status provides a clear "gate" between the MT and ST scheduling phases, making it easier to identify WOs that are ready for ST scheduling (Anonymous Expert 6, 2017).	[WO, Status] Scheduled (Proposed)
4.12 Final check that the Proposed Schedule is feasible	According to the Institute of Nuclear Power Operations (2010), it is good practice to carry out a final, physical check during the ST phase to ensure that all parts, tools and resources are definitely available before committing to the proposed schedule.	This final check is useful as it prevents technicians from starting tasks that they are unable to finish, which can waste a significant amount of time (Anonymous Expert 1, 2017; Anonymous Expert 7, 2017; Anonymous Expert 12, 2017). At this point, there may still be time to identify any issues and resolve them prior to execution; or alternatively, postpone the task before it is started (Institute of Nuclear Power Operations, 2010).	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
4.13 Load schedule to 100%	The schedule is loaded to its full capacity (which may or may not be 100% – see "Schedule Loading Strategy", step 4.06), considering any adjustments that need to be made based on: • The feasibility of the Proposed Schedule that was agreed during step 4.09, due to any issues that may have arisen since it was proposed, such as: ○ A sudden change in plant conditions or production priorities ○ Any problems found during step 4.12 (above) (Institute of Nuclear Power Operations, 2010) ○ External factors (e.g. weather may be a major factor in some contexts, e.g. offshore oil platform) (Anonymous Expert 7, 2017). • Any High Priority Emergent Work that has arisen in the ST (only if Option A was selected during step 4.04) (Keizers, Bertrand and Wessels, 2003; Campbell and Reyes-Picknell, 2006; Duffuaa and Raouf, 2015). • Any carry-over / unfinished work from the previous ST period (Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Hickman, 2011; Peters, 2014).	The level of uncertainty reduces as the execution date draws nearer; sufficient information is now available to construct a reliable, fully loaded schedule.	[WO, Field] Scheduled Start Date, Scheduled Finish Date [Scheduler, Function] View and adjust WO schedule dates and resource allocations (Prometheus Group, 2016; SAP, 2016)
4.14 Meet with the Production Team to confirm and commit to the Schedule	A final coordination meeting takes place with the Operations Team to confirm and commit to the ST schedule (i.e. the "Schedule Freeze Point") (Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Hickman, 2011; Peters, 2014; Shiver, 2017).	The purpose is to agree with production / operations that all required assets will be made available and fully prepared for maintenance in accordance with the schedule – failure to gain this commitment can result in execution delays, as shown in an oil and gas case study presented by Aoudia, Belmokhtar and Zwingelstein (2008). Regarding timescale for the ST "Freeze Point": Some industries prefer to freeze the schedule several weeks in advance (e.g. 6 weeks in one case), to achieve a more predictable upcoming workload, and give more time for preparation activities (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017). Others prefer to freeze the schedule very close to the date of execution (i.e. 1 week or even 1 day before) to allow more flexibility to accommodate changing priorities; this is the better choice for industries which can experience high volumes of unpredictable emergent work (Monsanto, 2007; Hickman, 2011; Anonymous Expert 1, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 9, 2017; Shiver, 2017). It can be very disruptive if the schedule freeze point is set incorrectly: in one highly reactive case, the freeze point was set too far in advance (i.e. 12 weeks), which meant that on the day of execution there were huge volumes of additional emergent work to accommodate, essentially rendering the schedule meaningless (Anonymous Expert 12, 2017).	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
4.15 Assign named individuals to each task	Once the ST schedule is confirmed, individual technicians are allocated to each maintenance activity, depending on their availability and competencies.	Multiple sources agree that individual allocation should take place during the ST period (Howard, 2004; Campbell and Reyes-Picknell, 2006; Al-Turki et al., 2014; Peters, 2014), but there are several options regarding who should make the assignments: **[Option A]** The most common approach is for the Maintenance Supervisor to make the assignments, because they are best placed to understand their team member's availability, skills and experience (Westerkamp, 1998; Hickman, 2011; Al-Turki et al., 2014; Duffuaa and Raouf, 2015; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). In contexts where there are multiple supervisors in a maintenance department (e.g. one for each team or area), it may be necessary to specify the appropriate supervisor within each WO, so that the CMMS clearly shows who is responsible for the allocation in each case (Anonymous Expert 11, 2017). This also helps during WO closure, to show which supervisor is responsible for reviewing and closing out the WO. **[Option B]** An alternative is for the scheduler to assign individual technicians to tasks, but there is some risk with this approach that the scheduler may not have sufficient knowledge of the team's skills, experience and immediate availability – however this approach is often necessary in highly reactive environments where the Team Leader is simply too busy fire-fighting (Peters, 2014; Anonymous Expert 6, 2017; Anonymous Expert 8, 2017). **[Option C]** The third option is for self-governing teams of technicians to determine their own assignments, which may be appropriate for smaller, more autonomous maintenance teams in organisations with very flat structures (Keizers, Bertrand and Wessels, 2003; Campbell and Reyes-Picknell, 2006). The concept is to reduce the number of supervisors to give technicians more accountability and ownership of plant performance (Anonymous Expert 3, 2017; Anonymous Expert 8, 2017). However, one potential disadvantage of this approach is that technicians may be tempted to assign themselves to the easiest tasks first, rather than the most urgent ones (Anonymous Expert 3, 2017; Anonymous Expert 6, 2017).	[WO, Field] Job Step Assignment = (individual) [Scheduler, Function] View and adjust WO Job Step Assignments (Prometheus Group, 2016; SAP, 2016) [WO, Field] Supervisor
4.16 [Optional] Prepare Fill-in Work List	A list of additional, low-priority "fill-in" tasks is compiled alongside the schedule, for technicians to freely work on if they finish their allocated tasks early. These are identified in the CMMS via a specific priority class so that they are clearly visible (Institute of Nuclear Power Operations, 2010; Hickman, 2011; Anonymous Expert 11, 2017).	To maximise the productivity of the system – i.e. do as much work as possible with a given amount of resource.	[WO, Field] Priority = Fill-in Work
4.17 Change WO Status = "Scheduled (Confirmed)"	The WO Status is changed to Scheduled (Confirmed).	To indicate that the Scheduled Start and Finish dates have been confirmed by all stakeholders. The work is now ready for execution (Monsanto, 2007; British Standards Institute, 2009; Hickman, 2011; Duffuaa and Raouf, 2015).	[WO, Status] Scheduled (Confirmed)

Process Step	Definition	Justification	CMMS Implementation Spec.
4.18 [Optional] Schedule Change Control Process	Any changes made to the schedule beyond the "Freeze" point must go through a formal change control process, with sign off required from key stakeholders (e.g. production and maintenance supervisors) (Anonymous Expert 4, 2017; Anonymous Expert 7, 2017).	This will ensure that any changes are properly communicated and agreed by all interested parties. According to industry experts (see submission 6, section 3.2.5) this step is good practice in the majority of cases, but it may be ignored in contexts where there is no desire to rigidly control the schedule scope. In the author's view, if the schedule is not rigidly controlled, then there is a risk that people ignore it and choose their own priorities instead, which undermines the entire MD process.	N/A
4.19 Review Schedule Progress	The maintenance schedule should be reviewed on a routine basis to monitor job progress and resolve any issues that could delay execution (Duffuaa et al., 2001; Hickman, 2011; Institute of Nuclear Power Operations, 2010; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Eaton, 20117; Anonymous Expert 7, 2017; Anonymous Expert 12, 2017): • At the start of each working day; • At the close of each working day; • Post Execution Review.	Meeting at the start of each working day is essential in a 24-hour operational environment, to highlight any issues that have arisen overnight that could delay execution, such as additional High Priority Emergent Work or changing production priorities (Peters, 2014). A key input is therefore from the Production Supervisor (see step 5.04). It is also useful to hold a second meeting at the end of each working day, to allow feedback on schedule progress to be communicated to all stakeholders (see step 5.22) (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Eaton, 20117; Anonymous Expert 7, 2017; Anonymous Expert 12, 2017). The purpose of the Post Execution Review is to assess schedule compliance – i.e. to check if the agreed scope was delivered in the specific ST period (Institute of Nuclear Power Operations, 2010). If any tasks were not completed to schedule it is important to determine why, so that improvements can be made for next time (Anonymous Expert 8, 2017; Anonymous Expert 9, 2017). The frequency of these review meetings should match the timescale of the "short term" scheduling phase (i.e. how far the freeze point is in advance of execution) (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017).	N/A

Framework Section 5 – Execution



Process Step	Definition	Justification	CMMS Implementation Spec.
5.01 Ensure upcoming scheduled work is visible and accessible to all Work Teams	Ensure that Scheduled Maintenance is visible and accessible to all work teams (Monsanto, 2007; Institute of Nuclear Power Operations, 2010; Peters, 2014), using either: - **[Option A]** Notice board / Display screen - **[Option B]** Individual Work List (printed or via a mobile device)	**[Option A]** A published schedule displayed on a notice board / display screen provides the entire team (including both production and maintenance) with essential visibility and awareness of upcoming assignments for each individual and for their colleagues, as well as who is absent / away on training etc.; this is a vital communication tool that allows everyone to be better prepared, which reduces execution delays (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). **[Option B]** An individual Work List can be provided to each technician, which simply lists the upcoming tasks that they have been assigned to; this is best used in conjunction with a visual published schedule, because it does not provide a holistic view of the entire team's activities – however it is valuable for ensuring that technicians fully understand their own assignments (Monsanto, 2007; Anonymous Expert 7, 2017; Anonymous Expert 11, 2017). This personal work list option is most effective when technicians are supplied with a mobile device which can provide the information electronically; this is especially useful in a utilities / infrastructure context where technicians are spread over a large geographical area, and need to receive their work assignments remotely (Anonymous Expert 11, 2017; Lorenzi, 2017).	[Scheduler, Function] Display schedule, per Work Team or Area (Prometheus Group, 2016; SAP, 2016) [CMMS, Function] Individual Work List available via mobile device, with suitable user interface
5.02 Review Upcoming Scheduled Work	The Production Team review all maintenance activities scheduled over the Short Term period. As with step 5.01, the method of accessing this information could either be via a published schedule on display, or via a list of WOs requiring permits (Anonymous Expert 5, 2017).	So that they can carry out all of the required preparation activities in advance of execution (i.e. isolation, decontamination, permit to work).	[Scheduler, Function] Display schedule, per Work Team or Area (Prometheus Group, 2016; SAP, 2016)
5.03 Preparation for Maintenance	The Production Team carry out the required preparation activities for all upcoming scheduled maintenance, in advance of execution (e.g. during the previous night shift) including: • Prepare plant isolation & decontamination • Prepare Risk Assessment & Permit (British Standards Institute, 2004; Sahoo, 2008; Institute of Nuclear Power Operations, 2010; Peters, 2014; British Standards Institute, 2015a)	If all preparation work is completed in advance, then maintenance activities can begin at the scheduled start time without delay. In many cases, it is not practicable to isolate plant several days before work starts, because production critical items need to stay online as long as possible; however, it saves valuable time during execution if the isolation scope is prepared in advance (e.g. 1 week before) with the isolation itself taking place much closer to the start of work (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017).	N/A
5.04 Conduct Start of Work Day Meeting	At the start of each working day, before execution begins, a coordination meeting is held between Production and Maintenance Team members.	To confirm that preparation tasks are complete and that scheduled maintenance can commence (Peters, 2014). If High Priority Emergent Work is scheduled (i.e. step 4.04, Option A), check for any new incidents that have arisen since the schedule was published and accommodate them by postponing low priority work (Institute of Nuclear Power Operations, 2010; Al-Turki et al., 2014; Duffuaa and Raouf, 2015).	N/A
5.05 Execute tasks in accordance with the Published Schedule	Maintenance tasks are executed as and when specified by the published schedule.	It is essential that the schedule is followed and that no additional work takes place outside of the MD process, to ensure that limited resources are only utilised to carry out approved work (Campbell and Reyes-Picknell, 2006; Peters, 2014; Duffuaa and Raouf, 2015).	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
5.06 Issue & Accept Permit before starting work	Before starting work, the Operations Team issue a Work Permit, which is accepted by the Maintenance Team (Peters, 2014). **[Optional]** Permit Systems can be paper based or CMMS based, in which case they are linked to the relevant WO; this reduces paperwork and ensures that the WO cannot be released for execution until the permit is electronically issued (Anonymous Expert 7, 2017).	This is an essential part of work control, particularly in high hazard environments. Both parties confirm that the plant has been isolated, made safe and control has been handed over to the Maintenance Team.	[WO, Function] Electronic Permit to Work
5.07 WOs are assigned to technicians by their supervisor	For work that is not planned and scheduled, but skips directly to execution (i.e. if Option B is selected in step 3.01), it is the supervisor's responsibility to distribute the required work amongst their team (according to task Due Date / Priority and resource competency) (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017; Anonymous Expert 9, 2017; Anonymous Expert 12, 2017). This could be via a printed personal work list for each technician, or via a mobile device if such technology is available for providing this information electronically; this is especially useful in a utilities / infrastructure context where technicians are spread over a large geographical area, and need to receive their work assignments remotely (Anonymous Expert 11, 2017).	As discussed earlier in step 3.01, skipping planning and scheduling is not recommended in more reactive / maintenance-intensive environments, with high workloads that place considerable pressure on a limited pool of labour resources (Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 5, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). There is a clear negative effect on performance if planning and scheduling is neglected, and resources are consequently poorly coordinated and unable to deliver the required work, as shown by Samaranayake and Kiridena (2012) in their study of aircraft maintenance. However, it is appropriate in contexts where there is no value in detailed planning and scheduling, because resource availability is not the limitation (it may be another factor, such as cost) – for example if maintenance execution is entirely (or partially) outsourced with a flexible labour contract that can expand to meet peaks in demand (Anonymous Expert 10, 2017).	[CMMS, Function] Individual Work List available via mobile device, with suitable user interface
5.08 [Optional] Fill-in Work List	When technicians complete all of their assigned work, they can move on to a communal list of low priority fill-in tasks (if optional step 4.16 is utilised). These are identified in the CMMS via a specific priority class so that they are clearly visible (Institute of Nuclear Power Operations, 2010; Hickman, 2011; Anonymous Expert 11, 2017).	To maximise the productivity of the system – i.e. do as much work as possible with a given amount of resource.	[WO, Field] Priority = Fill-in Work

Process Step	Definition	Justification	CMMS Implementation Spec.
5.09 Develop a Safe & Effective Method	A safe and effective method is developed for the task by the technician responsible for execution: - Carry out a site visit - Assess any risks - Develop clear instructions A detailed Risk Assessment and Method Statement (RAMS) must be developed for every task – its purpose is to provide a safe and effective method / procedure with detailed instructions. This document is a regulatory requirement in many contexts, to ensure that safety risks are adequately controlled. The finished RAMS will require review and approval by a competent person prior to issue (Institute of Nuclear Power Operations, 2010; Peters, 2014; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 12, 2017). This step will only be applicable if WO planning and scheduling (i.e. sections 3 and 4) have been skipped, either by selecting Option B in step 3.01, or Option B in step 2.25. Further details are available in one of the skipped planning steps, i.e. 3.04; to avoid repetition only the core information has been included here.	Note that even if Option B is selected in step 2.25 or step 3.01, planning can never be completely "skipped", as some elements cannot be avoided (i.e. risks still need to be assessed, a safe method needs to be developed with clear written instructions, plant isolations must to be requested and coordinated, parts must be ordered / retrieved from the stores etc.). The result is that these planning activities are passed on to the technician, who will essentially have to plan their own work, outside of the CMMS, immediately prior to execution (Kherun et al., 2002; Suttell, 2005; Ismail, 2014). This effectively slows down the execution of each task, and reduces productivity or "Wrench Time" (i.e. the % of a technician's day spent actually doing maintenance) (Westerkamp, 1998; Peters, 2014; Shafeek, 2014). Fundamentally, technicians are skilled personnel employed to execute maintenance tasks, and as much of their time as possible should be dedicated to this – not spent at a computer writing methods statements, or searching the stores looking for spares. A dedicated planner should do the planning, to facilitate the productivity of the technicians (Westerkamp, 1998; Peters, 2014; Shafeek, 2014; Anonymous Expert 1, 2017; Anonymous Expert 3, 2017; Anonymous Expert 4, 2017; Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). It is only recommended to skip sections 3 and 4 and have technicians do their own planning, in contexts with low, predictable workloads, or with high levels of outsourcing (Anonymous Expert 10, 2017; Anonymous Expert 11, 2017).	N/A
5.10 Acquire Parts and Tools	If the task requires parts and / tools, the technician must acquire them prior to starting work.	As with step 5.09 above, if planning is skipped then the technician will have to obtain their own parts and tools on the day of execution; they essentially need to follow steps 3.17 – 3.24 by themselves before they can start work, which greatly reduces productivity or "Wrench Time". This may be acceptable if everything required is in stock and is easily retrievable, but if parts need to be procured then this approach will cause significant delays to the WO start time.	N/A
5.11 Preparation for Maintenance	Just as in step 5.03, essential preparation activities must be completed before maintenance can commence, i.e.: • Prepare plant isolation & decontamination • Prepare Risk Assessment & Permit	The difference between this step and 5.03, is that in this case WOs have not been scheduled, so there is no advance warning for the Production Team. Preparation activities cannot take place in advance, and therefore they will cause a delay to the start time of the job, which reduces productivity or "Wrench Time".	N/A
5.12 Problem Encountered?	A problem is encountered during execution which could cause the task to take longer than planned; this could have a knock-on effect which delays the start of other scheduled tasks (i.e. a "schedule break") (Institute of Nuclear Power Operations, 2010; Peters, 2014).	It is necessary to include execution problems in this framework so that they can be managed, to reduce their impact on the schedule.	N/A
5.13 Additional Unplanned Materials required (available in stock)	Additional parts are required that were not part of the original WO plan. They are available in stock, therefore this problem does not cause a schedule break.	If additional unplanned parts are required, and those parts are in stock, it should be possible to acquire them quickly enough and still complete the work on time, provided that the goods issue process is suitably efficient (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017). As described in step 3.23, RFID / barcode scanning technology is helpful in this regard (Anonymous Expert 6, 2017).	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
5.14 Withdraw Materials and continue task	The Maintenance Technician withdraws the additional parts from stock; they are issued to the WO (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017).	A Goods Issue to the WO is required to ensure that stock levels are kept up to date, and to ensure that the cost of the parts is allocated to the correct maintenance task (rather than against a generic Cost Centre Code) (Anonymous Expert 8, 2017). **[Optional]** Barcode scanning or RFID (Radio-frequency Identification) functionality can be utilised to reduce the time taken for this step and to reduce data input errors (Teresko, 2003; Mele, 2007; Canaday, 2011; Anonymous Expert 6, 2017).	[Material, Function] Goods Issue to WO
5.15 A significant problem occurs which causes a schedule break	Possible problems: • Inadequate planned duration • Scope growth beyond Permit intent • Procedure invalid • Parts unavailable (Non-Stock)	It is possible for additional scope to arise during execution, meaning that it is no longer possible to complete the task on time and avoid a schedule break (Institute of Nuclear Power Operations, 2010; Peters, 2014; Duffuaa and Raouf, 2015).	N/A
5.16 Notify person with the authority to break the schedule	The technician must notify somebody with authority that a schedule break is imminent, so that action can be taken. There are several options regarding who should be responsible for resolving schedule break issues: • **[Option A]** The Maintenance Supervisor (i.e. whoever is responsible for the technicians) (Institute of Nuclear Power Operations, 2010; Peters, 2014) • **[Option B]** The Schedule Manager / Coordinator (i.e. whoever is responsible for the schedule) (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017) • **[Option C]** Production Manager (i.e. whoever is responsible for production performance) (Peters, 2014). • **[Option D]** Technicians should be able to self-approve schedule breaks, as long as the additional scope is recorded afterwards (Duffuaa and Raouf, 2015).	Each approach has its own pros and cons: as the seniority of the approver increases, there is tighter control over the process and perhaps a greater respect for the scheduled deadlines, but perhaps less flexibility or capability to adapt to rapidly changing circumstances. The decision will depend on the nature of the organisation and their overall approach to MD – i.e. whether control / predictability is valued over flexibility / responsiveness. Another approach is for the required level of authority to vary from task to task, depending on the magnitude of the delay, or on the importance of the work (Institute of Nuclear Power Operations, 2010).	N/A
5.17 Authorise use of additional resources to avoid a schedule break	The use of additional resources is authorised to complete the task on time (Peters, 2014): - **[Option A]** Overtime / Flexible Working - **[Option B]** External Contractors This will enable the additional work scope to be completed without breaking the schedule, but it will result in an additional financial cost. A decision must be made to determine if this cost is justified.	Option A involves utilising additional hours from existing resources (either via paid overtime or via flexible working arrangements, depending on company policy and employee contracts) (Anonymous Expert 8, 2017). Option B involves hiring additional external resources, if suitable service contracts are in place.	N/A
5.18 Postpone scheduled work	A decision is made that the additional cost of overtime / contract resource is not justified, therefore the work will be postponed and returned to the planning stage (i.e. section 3).	So that it can be re-planned with the additional scope included, and re-scheduled for execution at a later date (Institute of Nuclear Power Operations, 2010; Duffuaa and Raouf, 2015; Rødseth and Schjølberg, 2017). Ensure that the part-finished job is left in a safe condition – the permit may require extending and should be left on display to show that the asset cannot be returned to service (Anonymous Expert 6, 2017).	N/A
5.19 Inform Shift Manager	The Operations Shift Manager / Team Leader is informed of the schedule break.	The break in the maintenance schedule could have an effect on operational activities, therefore it is important to notify this key stakeholder (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 7, 2017)	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
5.20 Change WO Status = "Return to Planning"	The WO Status is changed to "Return to Planning", which sends it back through sections 3 and 4 so that the plan can be adjusted and re-scheduled for execution at a later date – a comment should be included in the WO to describe the additional required scope (Institute of Nuclear Power Operations, 2010; Duffuaa and Raouf, 2015). The wording of this status is deliberately different to the usual "Awaiting Planning" Status, so that WOs that caused schedule breaks can be separately quantified so that performance can be monitored and improved (Anonymous Expert 7, 2017; Anonymous Expert 8, 2017).	**[Optional]** According to industry experts (see submission 6, section 3.2.6), it is useful if the CMMS is configured to require a "Reason Code" when the "Return to Planning" Status is selected, to explain why the task was postponed (e.g. parts not available, permit not ready, insufficient time allocated etc.). This data can then be trended to track common planning errors, so that improvements can be made to prevent recurrence (Anonymous Expert 2, 2017).	[WO, Status] Return to Planning [WO, Field] Reason Code [WO, Function] Reason Code becomes mandatory if "Return to Planning" Status is selected
5.21 Update Maintenance Schedule to reflect changes	The Maintenance Schedule is amended to include the changes made above. In some contexts the schedule break authority may not actually make the updates to the schedule – it is more likely to be a scheduler, under the authority's instruction (Anonymous Expert 7, 2017).	The schedule must be kept up to date so tha it accurately displays all ongoing work (Institute of Nuclear Power Operations, 2010).	[Graphical Scheduler, Function] View and adjust WO schedule dates and resource allocations (Prometheus Group, 2016; SAP, 2016)
5.22 Feed back changes at daily schedule review meeting	Ensure that any changes to the schedule are discussed at the "Close of Day" scheduling meeting (see step 4.19).	It is useful to hold a review meeting at the end of each working day, to allow feedback on schedule progress to be communicated to all stakeholders (see step 5.16) (Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017).	N/A
5.23 Complete Task	Work execution is completed. Clean up the work area (British Standards Institute, 2004; Institute of Nuclear Power Operations, 2010; Peters, 2014).	To maintain housekeeping standards.	N/A
5.24 Perform Quality Check	A quality check is performed for the completed task, involving the maintenance technician, a member of the operations team (i.e. the customer), and the Maintenance Team Leader / Supervisor (Kherun et al., 2002; British Standards Institute, 2009; Shafeek, 2014). The level of detail in the quality check should be appropriate based on the level of risk inherent in the task (i.e. increased scrutiny for new tasks, critical plant, outsourced labour etc.) (Anonymous Expert 5, 2017; Anonymous Expert 12, 2017).	• To verify that the work was completed according to the agreed scope (Institute of Nuclear Power Operations, 2010) • To test the equipment function and ensure that it is fit for service (Peters, 2014) • To test equipment integrity to ensure safety and reliability prior to the re-energisation of plant (Anonymous Expert 8, 2017).	N/A
5.25 [Optional] Create WO Request Type = "Rework"	If a quality issue is found and rework is required to rectify it, then a WO Request is raised (Type = "Rework").	Utilising a separate WO Request Type makes it possible to quantify rework (i.e. just perform a count of the number of requests) (Anonymous Expert 4, 2017). The alternative is to state the term "rework" in the WO description, but this creates less reliable data, as it could be misspelled and then excluded from the count (Anonymous Expert 1, 2017). Alternatively, if there is no desire to measure the quantity of rework, when a quality issue arises it can be simply addressed via a toolbox talk to raise awareness of the issue and minimise recurrence (Anonymous Expert 5, 2017).	[WO Request, Field] WO Request Type = Rework

Process Step	Definition	Justification	CMMS Implementation Spec.
5.26 Review Job Method and Purpose	For every task that is completed, the technician(s) involved should review: • The Job Method to determine if there is a more effective way of executing the task next time, or any improvement required to the clarity of the instructions (Institute of Nuclear Power Operations, 2010; Duffuaa and Raouf, 2015). • The purpose of the task itself, to determine if its scope and frequency are valid and appropriate (British Standards Institute, 2004; Monsanto, 2007; Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 3, 2017; Anonymous Expert 6, 2017).	The technician(s) carrying out the work are well-placed to offer valid feedback on both the effectiveness of the Job Method (developed in step 3.04 / 5.09) and on the validity of the maintenance specified in the TBOM (see step 1.14) – e.g. could certain inspections afford to be less frequent because asset condition is not deteriorating? Are some activities unnecessarily invasive and result in over-maintaining? This review will identify such improvement opportunities, which will be formally submitted in Section 6.	N/A
5.27 Hand plant back to Production	Control of the plant is handed back to the Production Team; the Permit to Work is cancelled (Institute of Nuclear Power Operations, 2010; Peters, 2014). As with step 5.06, permit Systems can be paper based or CMMS based to reduce paperwork (Anonymous Expert 7, 2017).	This is an essential part of work control, particularly in high hazard environments. Both parties confirm that the maintenance is complete and that no further work will take place, before control is handed back to the Production Team and the plant is re-energised.	[WO, Function] Electronic Permit to Work
5.28 [Optional] Create Retroactive Work Order	If the task was executed without a WO (i.e. if Option B was selected in step 2.25, or if "quick fixes" were permitted at step 2.02), then one must be created retroactively.	In contexts where it is permitted for work to take place without a WO (e.g. High Priority Emergent Work), then it is important to create one retroactively so that maintenance history can still be fully recorded (Hickman, 2011; Anonymous Expert 2, 2017; Anonymous Expert 4, 2017; Anonymous Expert 5, 2017; Anonymous Expert 6, 2017; Anonymous Expert 9, 2017; Anonymous Expert 10, 2017; Anonymous Expert 11, 2017; Anonymous Expert 12, 2017). See step 2.25 for further guidance.	[WO, Type] Retroactive
5.29 Confirm Work Complete	The technician changes the WO Status to show that the maintenance task has been completed (Hickman, 2011; Ismail, 2014; Ramskill, 2014; British Standards Institute, 2015b; Duffuaa and Raouf, 2015). There should also be an option to mark the WO as partially complete (perhaps with a percentage to indicate current progress); this is necessary in a shift-work context to enable different work crews to communicate progress for tasks that span multiple shift periods (Hickman, 2011; Anonymous Expert 12, 2017).	So that completed work can be tracked and measured, to provide a record of work performed (British Standards Institute, 2004; Wulff, 2005; British Standards Institute, 2009; Shafeek, 2014). **[Optional]** This step is a good candidate for data entry via a mobile device in the field, which will enable the technician to enter data without returning to the office; provided that the CMMS is be capable of providing a suitable user interface (Emmanouilidis et al., 2009; Anonymous Expert 11, 2017; Anonymous Expert 10, 2017; Lorenzi, 2017). This is particularly useful in contexts in which assets are spread over a large geographical area, so that technicians can access the CMMS remotely to enter and retrieve data in a timely manner (Anonymous Expert 11, 2017).	[WO, Status] Work Complete [WO, Status] Work Partially Complete [WO, Field] % Complete [CMMS, Function] Work Completion / Partial Completion via mobile device, with suitable user interface

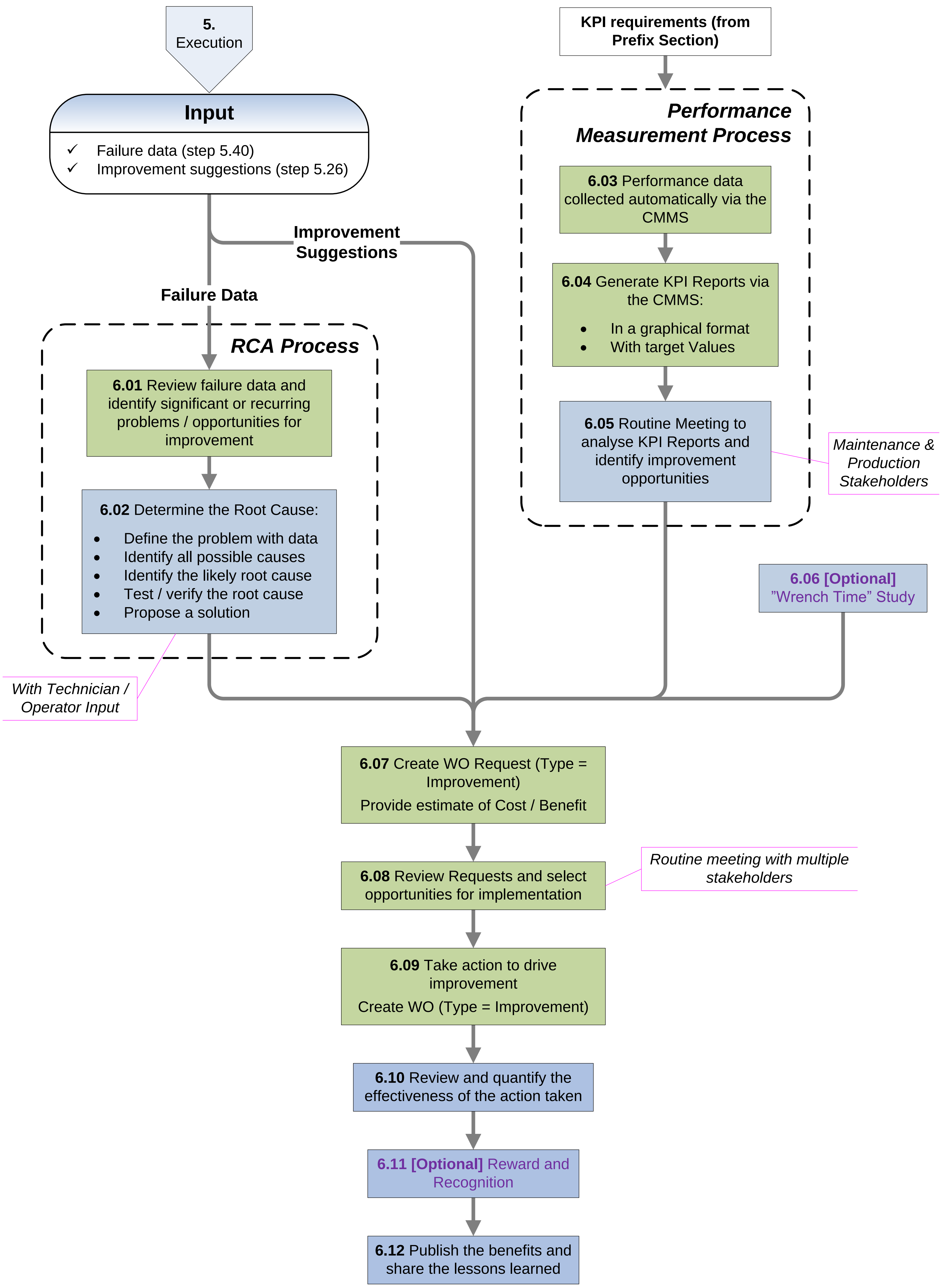
Process Step	Definition	Justification	CMMS Implementation Spec.
5.30 [Optional] Confirm Actual Duration	Record the actual time taken to complete the work (British Standards Institute, 2004; Wulff, 2005; Campbell and Reyes-Picknell, 2006; Monsanto, 2007; Ramskill, 2014; Shafeek, 2014). In contexts where temporary contract resource is utilised for execution, it may be necessary to record actual durations manually using paper timesheets, which are then transcribed into the CMMS by an administrator, because contractors often do not have access to the CMMS (Anonymous Expert 12, 2017). This step is also a good candidate for data entry via a mobile device in the field, which will enable the technician to enter data without returning to the office; provided that the CMMS is be capable of providing a suitable user interface (Anonymous Expert 10, 2017; Anonymous Expert 11, 2017). This is particularly useful in contexts in which assets are spread over a large geographical area, so that technicians can access the CMMS remotely to enter and retrieve data in a timely manner (Anonymous Expert 11, 2017). An alternative method for recording task duration is to configure the CMMS to calculate it automatically. Technicians essentially press a "Work Started" button on their mobile device when they start a new task (which changes the WO Status in the background), and then press the "Complete" button when finished with the job. The CMMS will automatically record the time taken between the two actions as the Actual Duration. This approach simplifies the WO closure process and decreases the scope for human error by reducing the amount of data entry required (Anonymous Expert 11, 2017).	To enable comparison with the estimated task duration and the development of historical averages (see step 3.08) (Campbell and Reyes-Picknell, 2006; Lopez and Centeno, 2006; Peters, 2014). Be aware that in some sectors, technicians can become suspicious if asked to record the time taken to complete work – they may think that the purpose is to measure how hard they are working, and feel pressured to "book 8 hours every day". It is important to ensure they understand that the reason is to improve the accuracy of job duration estimates, so that scheduling is more reliable (Anonymous Expert 3, 2017; Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017). Actual Duration data can also be used to calculate the total amount of maintenance work done per year – a useful figure which can be used to justify resource levels to senior management (Anonymous Expert 11, 2017). This step can be skipped in contexts that are not resource-limited, and where detailed planning and scheduling are consequently skipped (i.e. step 3.01, Option B); in such cases there is no value in recording actual duration (Anonymous Expert 10, 2017).	[WO, Field] Actual Duration = (hours) [CMMS, Function] Actual Duration entry via mobile device, with suitable user interface [CMMS, Function] "Work Started" and "Work Complete" buttons available via mobile device, linked to corresponding WO Status [WO, Status] Work Started [WO, Function] Actual Duration calculated automatically using time between "Work Started" and "Work Complete" Status
5.31 [Optional] If Actual Duration > Planned Duration, Enter Reason Code	If the Actual Duration of the task was longer than the Planned Duration, the technician explains why by selecting an option from the Reason Code field (e.g. additional parts required, delays obtaining Permit, waiting for isolations etc.)	It is beneficial if task delays are quantified against specific "Reason Codes", so that the most common causes of delay can be easily identified and improved to make execution more productive in the future (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 9, 2017). The Reason codes used in this step will be the same as those used in step 5.20 (i.e. for a schedule break), the only difference will be the magnitude of the delay.	[WO, Field] Reason Code [WO, Function] Reason Code becomes mandatory if Actual Duration > Planned Duration (by a defined tolerance)
5.32 Confirm Parts and Services (if used)	Ensure that all parts and services (e.g. external contract labour) that were used are correctly listed in the WO, if applicable (British Standards Institute, 2004; Wulff, 2005; Sahoo, 2008; Lachance, 2012; Shafeek, 2014; Anonymous Expert 7, 2017).	So that maintenance expenditure is correctly recorded.	[WO, Field] Materials Used (Material ID Number, Quantity, Total Cost) [WO, Field] Services Used (Supplier, Description, Total Cost)
5.33 Return any unused parts to the stores	If any materials were not used during the maintenance task, there should be a process to manage returns and book the unused parts back into stock (Barry, Olsen and Petit, 2011; Anonymous Expert 7, 2017).	To ensure that the cost of unused materials is removed from the WO, and to ensure that stock levels are updated after the parts are returned to the shelf.	[Material Record, Function] Goods Return from WO

Process Step	Definition	Justification	CMMS Implementation Spec.
5.34 [Optional] Record Measurement Readings (if taken)	If the task was a condition monitoring activity, ensure that any relevant data is recorded in the CMMS against the corresponding Measurement Point defined in step 1.18. This step is optional because in some contexts it is quite common to completely outsource condition monitoring activities, and in such cases the data would be captured outside of the CMMS in a separate system (Anonymous Expert 1, 2017; Anonymous Expert 2, 2017; Anonymous Expert 5, 2017; Anonymous Expert 8, 2017). The disadvantage of this approach is that it prevents a subsequent WO Request from being raised automatically if an unacceptable condition is found (i.e. step 5.36 below).	Such data is essential for monitoring equipment condition, as part of a predictive maintenance program (British Standards Institute, 2004; Campbell and Reyes-Picknell, 2006; Shafeek, 2014; Duffuaa and Raouf, 2015). For qualitative readings (e.g. rating an asset's condition between say 1 and 5 following a visual inspection) it is helpful to provide clear visual guidelines to ensure consistency (i.e. example images for each condition grade); this is more practicable with a mobile device (Anonymous Expert 11, 2017).	[Measurement Point, Field] Measurement Value, recorded via WO and linked via Asset Record [CMMS, Function] Record Measurements via mobile device, with suitable user interface [Measurement Point, Function] Example images for each condition grade when recording qualitative measurements
5.35 [Optional] Comment on Work Done	The technician enters comments in the WO describing the work done and any issues found (Hickman, 2011; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017).	Industry experts agree (see submission 6, section 3.2.6) that these comments can form a key part of the asset's work history, which should be time stamped and locked / non-editable to provide a robust audit trail.	[WO, Field] Comments, time stamped, locked / non-editable
5.36 Raise WO Request (Type = Inspection Based)	If a defect or unacceptable condition was found during the task, then a WO Request should be raised (Hickman, 2011; Baker, Booth and Wilson, 2013; Peters, 2014; Shafeek, 2014). In these circumstances, a specific WO Request Type should be used (i.e. "Inspection Based") to enable defects discovered via routine inspection to be quantified, in order to measure the effectiveness of the preventive maintenance programme. The subsequent WO Request should also be linked back to the original inspection WO in the CMMS for reference (Anonymous Expert 7, 2017; Anonymous Expert 11, 2017).	The WO Request will formally request Emergent Work to rectify the unacceptable condition (see section 2). **[Optional]** Note that for condition monitoring activities (i.e. step 5.34), the CMMS can be configured to automatically raise a WO Request if Measurement Readings are outside of the pre-defined tolerance bands (as defined in the associated Measuring Point). This is useful for reducing the admin time taken to generate the WO Request, and for limiting the scope for human error in terms of data input (Cooper, 1998; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017).	[WO Request, Type] Inspection Based [WO Request, Field] Associated WOs [WO, Field] Associated WO Requests [WO, Function] Create WO Request, with Type = Inspection Based, if Measurement Value exceeds Tolerance Band as defined in Measuring Point. Readings and tolerances should be automatically typed into the WO Request Description Field.
5.37 [Optional] Change WO status = "Reviewed"	An authorised person (e.g. a supervisor or engineer) reviews the technician's work prior to WO closure to: - Verify that it was completed to the appropriate quality and safety standards (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 11, 2017). - Review the WO data and ensure that all mandatory fields have been filled in correctly (Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017). - View the latest measurement trends available for the asset to see if any remedial action needs to be taken (Monsanto, 2007; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017; Anonymous Expert 11, 2017).	Industry experts agree (see submission 6, section 3.2.6) that this approach is good practice for safety-critical tasks, and is a regulatory requirement in certain high-hazard industries.	[WO, Status] Reviewed [Measurement Point, Function] Display trend of Measurement Readings over time
5.38 Cost Settlement	Settle all costs associated with the WO, e.g. for parts or services used (Cooper, 1998; Shaw, 1998; Kherun et al., 2002; Shafeek, 2014).	Because the work has finished and no further costs are expected. Before the WO can be financially closed it is important to check that all associated invoices have been received, all suppliers have been paid, and all POs have been closed (Anonymous Expert 10, 2017).	[PO, Status] Closed
5.39 Change WO Status = "Financially Complete"	The WO Status is changed to "Financially Complete" (Suttell, 2005; Duffuaa and Raouf, 2015).	To show that all work is finished and all costs are settled.	[WO, Status] Financially Complete

Process Step	Definition	Justification	CMMS Implementation Spec.
5.40 Capture Failure Data	If the task was Emergent Work, then the WO Request associated with it is utilised to capture information about the failure event, i.e.: • Indicate if the asset failed in service – i.e. was it a complete breakdown or just a minor defect? (Campbell and Reyes-Picknell, 2006; Sahoo, 2008) • Record the Total Downtime incurred (Wulff, 2005; Sahoo, 2008; Shafeek, 2014), if applicable. • Select "Failure Codes", i.e. select the damage type and suspected cause from pre-defined lists (Ellis, 1998; Sahoo, 2008; Peters, 2014; Ramskill, 2014; Duffuaa and Raouf, 2015) This step is a good candidate for data entry via a mobile device in the field, which will enable the technician to enter data without returning to the office; provided that the CMMS is capable of providing a suitable user interface (Anonymous Expert 10, 2017; Anonymous Expert 11, 2017). Mobile devices are particularly useful in contexts in which assets are spread over a large geographical area, so that technicians can access the CMMS remotely to enter and retrieve data in a timely manner (Anonymous Expert 11, 2017).	This data is an essential input to the RCA process (Rooney, Heuvel and Lee, 2003; Hambleton, 2005; Barsalou, 2016), which is included in section 6. Failure codes are extremely valuable for trending recurring causes of downtime so that improvements can be made (Anonymous Expert 10, 2017). This data is collected shortly after the task has been completed, because at this stage the technician will have a good understanding of the nature of the failure and any likely causes. It is helpful if the list of failure codes matches the Failure Modes identified during step 1.14 – i.e. during TBOM Development (if the development methodology involves the determination of the asset's potential failure modes, as is common practice) (Anonymous Expert 11, 2017). This ensures that TBOMs can be reviewed more easily in the future (i.e. step 1.15) using the corresponding Failure Code data (e.g. frequency of failure for each mode). If this approach is taken, it is advised to include the option "New Failure Mode" in the list of failure codes: if a new failure mode is discovered during an inspection, this option can be selected and a comment can be left by the technician to explain the nature of the failure. This information can then be reviewed by an engineer so that the TBOM can potentially be revised (to include additional inspection activities to look for the failure in the future), and a corresponding new Failure Code can be added to the CMMS to track its frequency of occurrence in the future (Anonymous Expert 11, 2017). Aoudia, Belmokhtar and Zwingelstein (2008) describe a case from the oil and gas industry where historical equipment failure records were often incomplete. This was due to inadequate recording of data during WO Request closure, which caused difficulties during failure analysis and thus a lack of improvement. In some contexts technicians are reluctant to enter failure information because the process is complex or time-consuming. The solution is to ensure that data entry is as simple as possible – ensure that failure code options are kept to a minimum, and that they are relevant for the equipment type (this approach also makes trends more meaningful) (Anonymous Expert 10, 2017).	[WO Request, Field] WO Request Type = Breakdown [WO Request, Field] WO Request Type = Defect [WO Request, Field] Total Downtime Incurred [WO Request, Function] Total Downtime Incurred becomes mandatory if WO Request Type = Breakdown [WO Request, Field] Failure Code = catalogue of equipment-specific options
5.41 Change WO Request Status = "Problem Resolved"	The WO Request Status is changed to indicate that the problem has been resolved (Ismail, 2014).	So that it is removed from the list of outstanding defects.	[WO Request, Status] Problem Resolved
5.42 Inform initial Work Requester	The initiator of the request (i.e. from step 2.04) is informed that the problem has been resolved (Duffuaa and Raouf, 2015).	To ensure that a key stakeholder is informed of progress. Users are more likely to report failures in the future if they are made aware of the action that was taken to resolve them. This process can be automated in the CMMS, i.e. when the WO Request Status is changed "Problem Resolved", the requester receives an automated email (Anonymous Expert 2, 2017; Anonymous Expert 7, 2017).	[WO Request, Function] Requester is alerted by email when WO Request Status = Problem Resolved

Process Step	Definition	Justification	CMMS Implementation Spec.
	A note on end-user experience during WO Closure:	When configuring the CMMS, it is imperative to simplify and streamline the end user experience for technicians. WO and WO Request closure are the biggest interaction a technician will have with the CMMS – and ideally all steps in these areas can be achieved via a single input screen. This has multiple benefits: it reduces admin time (i.e. waste) enabling higher productivity (i.e. wrench time); reduces training requirements and the risk of human error; it improves user opinion and attitude towards the system, which is important for work ethic and data quality (Anonymous Expert 11, 2017).	

Framework Section 6 – Improvement



Process Step	Definition	Justification	CMMS Implementation Spec.
6.01 Review failure data and identify significant or recurring problems / opportunities for improvement	The Failure Data captured during WO Request closure (see step 5.40) is reviewed to identify any significant or recurring failures (Hambleton, 2005; Okes, 2005; Kidam and Hurme, 2013; Barsalou, 2016).	Suitable candidates include single events with significant consequences, such as plant downtime, or any small but chronic defects which accumulate over time (Latino, 2000; Shafeek, 2014; Jackson, 2016).	[Report] View WO Requests where Total Downtime Incurred > (User defined threshold) [Report] View total downtime accumulated over period (e.g. 12 months) per Asset Type, per Failure Code
6.02 Determine the Root Cause	Any significant or recurring failures found in step 6.01 are put forward for RCA, to determine the root cause and propose a suitable solution. RCA should be carried out by a multi-disciplined team including "hands on" technicians – i.e. the operator who found the original defect, and the technician who repaired it – to ensure that the problem is fully understood (Latino, 2000; Monsanto, 2007; Port, Ashun and Callaghan, 2011; Jackson, 2016; Anonymous Expert 6, 2017).	As discussed in submission 4, section 3.3, the specific RCA methodology to be used is outside of the scope of this framework and should be determined elsewhere. Regardless of the method chosen, according to the literature the following broad steps should be included: 1. Define the problem with data (i.e. step 6.01) 2. Identify all possible causes 3. Identify the likely root cause 4. Test / verify the root cause 5. Propose a solution (Katzel, 1996; Pylipow and Royall, 2001; British Standards Institute, 2004; Hambleton, 2005; Okes, 2005; Sharma and Sharma, 2010; Port, Ashun and Callaghan, 2011; Nailen, 2015; Barsalou, 2016; Jackson, 2016).	N/A
6.03 Performance data collected automatically via the CMMS	All data required for measuring performance is collected automatically via the CMMS (Kutucuoglu et al., 2001; British Standards Institute, 2007; Kumar et al., 2013). KPI requirements must be defined and configured beforehand (see framework Prefix section).	The generation of KPI reports automatically via the CMMS is essential – if this functionality is not available, reports have to be produced manually (using spreadsheets or similar) which is very time consuming and open to human error (Anonymous Expert 1, 2017). To enable automatic data collection, the CMMS must be configured in close alignment with the user's KPI requirements (Kherun et al., 2002; Duffuaa and Raouf, 2015; Parida et al., 2015), so that suitable input fields are available to capture the required source data (Barry and Stevens, 2011; Kumar et al., 2013; Parida et al., 2015). The framework Prefix section contains a comprehensive list of MD KPIs, extracted from various sources. Each KPI has its own configuration requirements clearly specified, and where applicable, the corresponding framework step(s) where the data input takes place. To enable automatic data collection by the CMMS, for each desired KPI ensure that the specified configuration requirements are included in the CMMS specification, and ensure that the corresponding mandatory framework steps are included in the tailored MD process.	See framework Prefix section
6.04 Generate KPI Reports via the CMMS	The required maintenance KPIs are produced via the CMMS (Shaw, 1998; Suttell, 2005; Sahoo, 2008; Duffuaa and Raouf, 2015).	KPIs should utilise a graphical format with target values to clearly highlight performance issues (Trindade and Nathan, 2008; Institute of Nuclear Power Operations, 2010; Kumar et al., 2013; Parida et al., 2015).	See framework Prefix section
6.05 Analyse KPI Reports	The KPI reports are analysed to identify improvement opportunities (Ellis, 1998; Kutucuoglu et al., 2001; British Standards Institute, 2007; Parida and Chattopadhyay, 2007; Barry and Stevens, 2011). This review should be carried out by both maintenance and production stakeholders (Anonymous Expert 8, 2017).	Analysis should take place at a regular frequency (British Standards Institute, 2007; Kumar et al., 2013; Shafeek, 2014). One way to ensure this is to hold a formal routine meeting (Institute of Nuclear Power Operations, 2010; Barry and Stevens, 2011).	N/A

Process Step	Definition	Justification	CMMS Implementation Spec.
6.06 [Optional] "Wrench Time" Study	Conduct periodic "Wrench Time" studies. Each study would involve observation of a (random) technician for a defined period of time (i.e. at least 1 full task), to measure and identify waste in the Maintenance Delivery process, so that this can be eliminated to improve productivity (Anonymous Expert 1, 2017).	"Wrench Time" is an important measure of maintenance productivity (i.e. the % of a technician's time per day spent actually doing maintenance, rather than wasted on admin, waiting for paperwork, waiting for parts, travelling to the job site etc.). However, according to industry experts (see submission 6, section 3.2.7), Wrench Time is very difficult to measure automatically using the CMMS, because the time taken for "waste" activities is not usually recorded – therefore, although potentially intrusive, direct observation is the only reliable way to obtain this information. Of course, technicians will need to be made aware that the intention of the study is to identify process bottlenecks and remove waste from their daily activities – not to check that they are working hard enough. This should clearly differentiate it from a "time and motion" study (which aims to determine task duration – see step 3.08).	N/A
6.07 Create WO Request (Type = Improvement)	Improvement opportunities from several different sources are managed via a single improvement process. The first step is to create a WO Request with the Type "Improvement" to register: • Any proposed solutions from the RCA process (see step 6.02) • Any improvement suggestions from the post-execution Job Method Review (see step 5.26) • Any improvement opportunities identified via analysis of KPI reports (see step 6.05) • Any improvement opportunities identified during "Wrench Time" studies (see step 6.06) This WO Request (Improvement) should capture the expected costs and benefits of each suggested improvement (Okes, 2005; Barry and Stevens, 2011). It is also helpful if benefits are clearly categorised (e.g. safety, reliability, or cost saving) to facilitate review and decision making (Anonymous Expert 4, 2017). Consider also that many risks and opportunities for improvement are non-financial; therefore it can be helpful to monetise these risks in order to enable a fair comparison during prioritisation (Anonymous Expert 4, 2017).	It is important to maintain a register of improvement opportunities so that they can be tracked throughout the improvement process; it is also essential that each item is given an owner with responsibility for progressing actions (Institute of Nuclear Power Operations, 2010; Barry and Stevens, 2011; Jackson, 2016). Typically, improvements are managed outside of the CMMS in a different system (Anonymous Expert 8, 2017; Anonymous Expert 9, 2017), but this framework suggests utilising the CMMS for this purpose by using a specific WO Request Type. This is beneficial because: - The existing screening and approval process (i.e. section 2) can be re-purposed for managing improvements as well as emergent work. - If technicians are expected to participate in improvement activities (as is common), then it is easy to plan and schedule these activities alongside other maintenance work, if a WO is utilised (Anonymous Expert 7, 2017). - By managing improvements via the CMMS, the quantity of improvements suggested, approved, and implemented etc. can be easily quantified and reported alongside other maintenance KPIs – which helps to monitor and justify expenditure on improvement activities (Anonymous Expert 6, 2017; Anonymous Expert 7, 2017; Anonymous Expert 8, 2017; Anonymous Expert 9, 2017).	[WO Request, Type] Improvement [WO Request (Improvement), Field] Owner [WO Request (Improvement), Field] Estimated Cost (£) [WO Request (Improvement), Field] Estimated Benefit (£) [WO Request (Improvement), Field] Benefit Category (e.g. safety, reliability, cost saving)
6.08 Prioritise and select opportunities for implementation	The list of outstanding improvement opportunities is reviewed and prioritised to determine which items should be implemented. The "Approval" Status within the WO Request can be utilised to show which items have been selected.	It is important to consider the estimated costs and benefits for each suggestion so that the improvement budget can be utilised most effectively (Okes, 2005; Barry and Stevens, 2011). The most effective way to ensure that improvement opportunities are properly assessed, prioritised and actioned, is to hold a formal, routine screening meeting for improvement requests, just as with defect requests in section 2, with the same stakeholders involved (Anonymous Expert 2, 2017; Anonymous Expert 10, 2017).	[WO Request, Field] Priority [WO Request, Status] Approved
6.09 Take action to drive improvement	The selected improvement opportunities are implemented, via a WO with the WO Type = "Improvement". If the improvement involves an asset change or modification, then an Asset Change Request will also be necessary (see step 1.01) to ensure that all risks are adequately assessed and approved by the Design Authority prior to implementation (Anonymous Expert 9, 2017; Anonymous Expert 12, 2017).	The WO is necessary to ensure that the work is adequately planned, controlled and executed through to completion (Monsanto, 2007; Barry and Stevens, 2011; Jackson, 2016). Without a robust process there is a risk that action is never taken and opportunities for improvement are missed (Latino, 2000; Institute of Nuclear Power Operations, 2010; Kumar et al., 2013).	[WO, Field] WO Type = Improvement

Process Step	Definition	Justification	CMMS Implementation Spec.
6.10 Review and quantify the effectiveness of the action taken	After implementation, the tangible benefits resulting from the action taken should be quantified.	To ensure that the potential improvement opportunity has been realised and to demonstrate the value created (Okes, 2005; Institute of Nuclear Power Operations, 2010; Barry and Stevens, 2011). Also to justify further investment in improvement activities (Simões, Gomes and Yasin, 2011; Kumar et al., 2013; Tätilä et al., 2014; Parida et al., 2015).	N/A
6.11 [Optional] Reward and Recognition	The individual who made the improvement suggestion or led the improvement action is rewarded financially, perhaps with a fixed percentage of the benefit realised by the improvement (e.g. 10%).	Such an incentive scheme can be adopted to encourage further improvement suggestions (Anonymous Expert 4, 2017).	N/A
6.12 Publish the benefits and share the lessons learned	Once the benefits have been quantified, they should be communicated to relevant stakeholders, such as budget holders or other sites within the organisation or the wider industry (if applicable) (Latino, 2000; Institute of Nuclear Power Operations, 2010; Kidam and Hurme, 2013; Jackson, 2016).	So that the benefits can be realised elsewhere.	N/A

Appendix E – Example Covering Letter sent to participants

(sent via email):

Hi [participant],
I was just handed your contact details by [anonymous] - he's a colleague of mine at [Sponsor company]; I believe he told you briefly about my research? I'm a doctoral student at the University of Warwick, researching best practices in Asset Management. I'm looking for participants from industry to share their views and experience.

If possible, I'm looking for a couple of hours of your time for a face-to-face discussion (at your site preferably), with a follow-up questionnaire by email sometime afterwards.
I'd be particularly interested to learn about your processes for the planning, control and delivery of maintenance, i.e.:

- *Asset Data Management*
- *Routine Maintenance*
- *Emergent Work Requests*
- *Screening and Approval*
- *Planning*
- *Scheduling*
- *Execution*
- *Root Cause Failure Analysis*
- *Performance Measurement*
- *Improvement*

Hopefully, there will be some benefit for you in this too, i.e.:
- *A chance to see how your practices in this area compare to others from around the world (I have reviewed 64 other maintenance processes so far from various industries), to confirm that you are doing the right things, or to identify potential improvements;*
- *A chance to contribute your practices and expertise to an international study;*
- *A copy of the end result of my research – which will be a very comprehensive framework and guidance for the planning, control and delivery of maintenance.*

Please do let me know when you are free any time after Christmas, I'm fairly flexible with regards to dates.
Looking forward to hearing from you.
Kind regards,

Phil Catt
p.j.catt@warwick.ac.uk

Appendix F – Participant Consent Form

WARWICK
THE UNIVERSITY OF WARWICK

BIOMEDICAL AND SCIENTIFIC RESEARCH ETHICS COMMITTEE CONSENT FORM

Title of Project: A Tailorable Framework for the Planning, Control and Delivery of Maintenance

Name of Researcher(s): Phil Catt

Please initial all boxes

1. I confirm that I have read and understand the information sheet dated **[11/01/17]** for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my legal rights being affected. ☐

3. I understand that the interview may be audio recorded. ☐

4. I understand that my data will be anonymised. ☐

5. I consent to the use of anonymised verbatim quotations in publications ☐

6. I agree to take part in the above study. ☐

________________	________________	________________
Name of Participant	Date	Signature
________________	________________	________________
Name of Researcher taking consent	Date	Signature

Version 2 [11/01/17]

Appendix G – Participant Information Leaflet

WARWICK
THE UNIVERSITY OF WARWICK

PARTICIPANT INFORMATION LEAFLET

Study Title: A Tailorable Framework for the Planning, Control and Delivery of Maintenance

Investigator(s): Phil Catt

Introduction

You are invited to take part in a study. Before you decide whether or not to take part, you need to understand why the study is being done and what it would involve for you. Please take the time to read the following information carefully.

(Part 1 tells you the purpose of the study and what will happen to you if you take part. Part 2 gives you more detailed information about the conduct of the study)

Please ask if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

PART 1

What is the study about?

This project aims to deliver a guidance framework that can be used by any organisation to develop an effective process for the planning, control and delivery of maintenance. The intent is for this framework to be highly detailed to ensure good performance, but also flexible so that it can be tailored to suit any context. It will also include guidance to facilitate decision making by the end user during the tailoring process.

64 existing maintenance planning and control processes from the academic literature have already been analysed and combined to produce a preliminary framework. The purpose of this study is to obtain expert opinion from industry on the completeness and suitability of this preliminary framework, and to enhance it further by incorporating industry best practice.

Do I have to take part?

It is entirely up to you to decide. We will describe the study and go through this information sheet, which we will give you to keep. If you choose to participate, we will ask you to sign a consent form to confirm that you have agreed to take part. You will be free to withdraw at any time, without giving a reason and this will not affect you or your circumstances in any way.

What will happen to me if I take part?

1. An initial face-to-face interview will be conducted by the researcher (at a location of your choosing). This will comprise of an open discussion to gather your opinion on the effectiveness of the preliminary framework, and how you think it could be improved. The interview may be audio-recorded, with your consent, and will take approximately 2 hours.
2. After all participants have been interviewed, each of their opinions and suggestions will be collected and analysed. You will then be asked to complete an online questionnaire, which will list all of the suggested changes to the framework from all participants (without names, so that participants cannot identify each other), and you will be asked to rate the effectiveness of each suggestion (i.e. whether you think the suggested change to the framework should be made or not).

What are the possible disadvantages, side effects, risks, and/or discomforts of taking part in this study?

The only impact from taking part in this study will be the use of your time, during the interview and during the completion of the online questionnaire.

What are the possible benefits of taking part in this study?

This time spent will hopefully provide the following benefits:

- A chance to see how your maintenance practices compare to others from around the world, to confirm that you are doing the right things, or to identify potential improvements;
- A chance to contribute your practices and expertise to an international study;
- A copy of the end result of the research – which will include a very comprehensive framework and guidance for the planning, control and delivery of maintenance.

Expenses and payments

No expenses or payments will be made; no travel will be required.

What will happen when the study ends?

The results of this study will be included in an Engineering Doctorate Innovation Report, a copy of which will be publically available in the University of Warwick library. Each participant will also be given a copy of this final innovation report. A summary of each participant's company and sector may be listed in this report, but not their names. This information will also not be directly linked to any recorded opinions, which will always be presented anonymously.

All study information (including research data, consent forms and administrative records) will be retained for a minimum of 10 years as electronic copies, stored on secure university servers.

Will my taking part be kept confidential?

Yes. We will follow strict ethical and legal practice and all information about you will be handled in confidence. Further details are included in Part 2.

What if there is a problem?

Any complaint about the way you have been dealt with during the study or any possible harm that you might suffer will be addressed. Detailed information is given in Part 2.

This concludes Part 1.

If the information in Part 1 has interested you and you are considering participation, please read the additional information in Part 2 before making any decision.

PART 2

Who is organising and funding the study?

This study is part of a doctorate degree course at the University of Warwick, and is organised by the doctoral student. The course is partially funded by the sponsor company, [redacted], and partially by the Engineering and Physical Sciences Research Council (EPSRC), a UK government agency for research funding.

What will happen if I don't want to carry on being part of the study?

Participation in this study is entirely voluntary. Refusal to participate will not affect you in any way. If you decide to take part in the study, you will need to sign a consent form, which states that you have given your consent to participate.

If you agree to participate, you may nevertheless withdraw from the study at any time without affecting you in any way.

You have the right to withdraw from the study completely and decline any further contact by study staff after you withdraw.

What if there is a problem?

This study is covered by the University of Warwick's insurance and indemnity cover. If you have an issue, please contact the organiser of the study:

Phil Catt, Doctoral Student (email: p.j.catt@warwick.ac.uk)

Who should I contact if I wish to make a complaint?

Any complaint about the way you have been dealt with during the study or any possible harm you might have suffered will be addressed. Please address your complaint to the person below, who is a senior University of Warwick official entirely independent of this study:

Head of Research Governance
Research & Impact Services
University House
University of Warwick
Coventry
CV4 8UW
Tel: 024 76 522746

Email: researchgovernance@warwick.ac.uk

Will my taking part be kept confidential?

Each participant's industry sector and company will be included in the final report, which is the only published part of the study. Participant names and job roles will be excluded. This information will be presented completely separately to any opinions, which will always be presented anonymously so that it is it not possible to link the two.

All study information (including research data, consent forms and administrative records) will be retained for a minimum of 10 years as electronic copies, stored on secure university servers.

What will happen to the results of the study?

The results of this study will be included in an Engineering Doctorate Innovation Report, a copy of which will be publically available in the University of Warwick library. Each participant will also be given a copy of this final innovation report. As stated above, each participant's company and sector may be listed in this report, but this information will not be directly linked to any opinion data, which will be presented anonymously. Verbatim quotations may also be featured in the report, but again these will remain anonymous.
The results of this study will be used to further develop the preliminary framework (as discussed in the "Aims/Objectives" section above), which will then be implemented and tested at a [redacted] site.

Who has reviewed the study?

This study has been reviewed and given favourable opinion by the University of Warwick's Biomedical and Scientific Research Ethics Committee (BSREC).
Reference Number: **REGO-2016-1901**

What if I want more information about the study?

If you have any questions about any aspect of the study, or your participation in it, not answered by this participant information leaflet, please contact:

Phil Catt, Doctoral Student (email: p.j.catt@warwick.ac.uk)
Dr Jeff Jones, Academic Supervisor (email: j.a.jones@warwick.ac.uk)

Thank you for taking the time to read this participant information leaflet.

Appendix H – Framework Implementation Impact Assessment: Full Questionnaire Responses

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
14								
E	**CMS (SAP / E-SOMS)**		0 point	1 point	3 points	4 points	points	Remarks
E.1	Is **EDP-support** (Electronic Data Processing) available in maintenance/operations for work order planning, controlling and analysing + shiftlog? (CMS - computerised management system)		no EDP support	single working places, in-house developed system with limited functions	CMM system, only interfaced to ERP	full integrated CMM system, for all relevant working places	4	Framework CMMS implementation spec ensures entire MD process is supported in full
E.2	Is there **only one system** for maintenance management in use?	x	no EDP support	parallel systems for different tasks (e.g. planning, payroll / time keeping system, purchasing, stock management, etc.), without interface	parallel systems for different tasks (e.g. planning, payroll / time keeping system, purchasing, stock management, etc.), with interface	leading system for main processes / tasks	4	SAP in use for all business streams
E.3	**Up-to-dateness** of the EDP systems / CMMS / E-SOMS?		no EDP support / old version, not any longer available	older than 7 years	older than 3 years	actual version	4	SAP ECC 6 installed - latest version
E.4	Has **proper training** been given to users?	x	no EDP support, no training	general information courses	nonrecurring training course	regular training with refreshing courses	4	Training programme in progress.
E.5	Are there **supporting resources** for the users available?		no / bad support	some support	via hot-line / acceptable support	good, personal support	4	Support / experts built into organisation
E.6	Is the system regarded to be **user friendly**?	x	no	by advanceded users		by all users	3	SAP user interface could be improved
E.7	What percentage of the **maintenance/operations personnel are using the system** for their job functions with a high level of proficiency?	x	less than 40 %	40 - 64 %	65 - 89 %	90 % or more	4	For those for whom it is relevant for their role
E.8	Is there a **plant / asset structure** in several levels (equipment tree)?		no asset structure	1 - 2 levels, cost centres	3-5 levels of functional location, cost centres, inventory numbers	tree structure with more than 5 levels, TAG-numbers, technical places & equipments	4	Framework step 1.05, option A implemented
E.9	Are all **asset / equipment TAG numbers** registered in the system?	x	not registered / no TAG numbers	only key critical equipments	only for new plants / assets	for all assets	4	This is the primary intent of framework section 1
E.10	Is it possible for the maintenance/operations teams to **track the actual status of jobs** (in preparation, in progress, finished, etc) in CMMS?	x	not possible		only for bigger jobs	general and possible at any time	4	WO statuses are built into all framework sections
E.11	Are **critical systems identified** in the CMMS system	x	no		Some critical equipment	All critical equipment	4	Optional framework step 1.09 implemented
E.12	Are the **relevant spare parts of the respective TAG numbers** filed in the system with corresponding material numbers?		no system	partly, for key critical equipment		yes, general and in use	4	Framework step 1.13 implemented
E.13	What percentage of all **service operations - performed by maintenance - utilize** a CMMS? *(service operations = maintenance, investments, shut down, modifications, etc.)*		less than 40 %	40 - 64 %	65 - 89 %	90 % or more	4	100% - as per implementation of framework step 2.25, option A
E.14	**What percentage of planable maintenance activities** (except high priority (prio 1) and rush (prio 2) orders) are **planned and scheduled** through a CMMS?		less than 40 %	40 - 64 %	65 - 89 %	90 % or more	4	100% - as per implementation of framework step 3.01, option A
E.15	Are CMMS data utilized, on a regular basis, **to make cost effective management decisions?**		no	few cases	sometimes	yes	4	This is the intent of framework section 6

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
27								
G	**Planning & Scheduling**		0 point	1 point	3 points	4 points	points	
G.1	Is there a system of work **requests / notifications and work orders**?		no system in use	no written information, only verbal communication	jobs are listed and communicated verbally	there is a system of written /electronic requests and work orders	4	This is the intent of framework section 2
G.2	What percent of production personnel **generate requests / notifications for work orders** for critical systems		less than 40 %	40 - 64 %	65 - 94 %	95 % or more	4	Framework step 2.04, option A implemented
G.3	Does the work request contain **all necessary information**?		no requests	only short description of work to be done	request mentions nearly all needed information	For critical systems all work requests are related to equipment numbers. Prioritization is ranked.	4	Framework step 2.04 implemented with appropriate mandatory fields
G.4	When **will work orders be created** for critical systems in CMMS?	x	not at all / after execution	most time after execution	only for planned jobs before execution	before execution of all kind of jobs including emergency breakdown.	4	Framework step 2.25, option A implemented
G.5	Is there a description / procedure how work order requests are systematically evaluated/selected to be executed or not (**work order selection - "gate keeping"**)?	x	no procedure	procedure exists, but not followed , everybody on production side can decide	definition of responsible persons, but not fully implemented procedure	lived procedure with definiton of responsible person(s)	4	This is the primary intent of framework section 2
G.6	Is there a description / procedure how work orders are systematically **prioritized?** (e.g. RBWS - Risk Base Work Selection)	x	it is random and based on emergency needs	is set by maintenance with minimal operations input	weekly in a joint production / maintenance meeting	daily in a joint production / maintenance meeting	4	Framework step 2.14, option A implemented
G.7	Is there a person on production / operations side who decides at which **"latest date"** the work order shall be finished for critical systems?	x	no procedure	procedure exists, but not followed , everybody on production side can decide	lived procedure with definiton of responsible person(s)	lived procedure, latest date for finishing preventive W.O. is pre-defined	4	As above. Latest dates are linked to priority selection
G.8	Testing of **critical equipment**. Is it scheduled automatically and reported back.	x	No scheduling for testing	Testing is scheduling in different system	All critical equipment is scheduled for testing, no reporting	All critical equipment is scheduled for testing and result is reported	4	Testing requirements come from step 1.24; result is reported at framework step 5.29
G.9	Is a **maintenance / service category** (like preventive maintenance, inspection, repair, modification, etc.) defined for each job for critical systems?		less than 64 %	65 - 94 %	95 % and more	All	4	100% - mandatory field. Optional framework step 2.18 implemented
G.10	What percent of work orders processed in the system are tied to an **equipment / asset number** (TAG-number) for critical systems?		less than 64 %	65 - 94 %	95 % and more	All	4	100% - mandatory field. Framework step 2.04 implemented
G.11	What percent of work orders are opened under a **priority** that would be identified as **emergency or high priority (prio 1)**?		more than 40 %	26 - 40 %	15 - 25 %	less than 15 %	4	8.6% as of 08/02/2018.
G.12	Is a satisfying part of **workload planned**? (Quality of planning & scheduling)		Firefighting, daily meetings, maintenance agrees with production on activities each day, < 30 % of maintenance workload is planned	Weekly schedule established, but followed < 50%	Weekly schedule established and followed between 50% and 80%	Weekly update of bi-weekly schedule with detailed plans, > 80% on weekly schedule.	4	100% of work is planned and scheduled: Framework step 2.25, option A implemented Framework step 3.01, option A implemented Framework step 4.04, option A implemented

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
27								
G	**Planning & Scheduling**		0 point	1 point	3 points	4 points	points	
G.13	Quality of longterm planning & scheduling? (at least for 1 -3 years)		Not available	Rough plan, not a living document	Only planned stops included	1 to 3 - 5 year plan available with planned stops, critical inspections and projects, detailed and used as input for bi-weekly plan and turnaround plans	4	Framework step 4.01 and optional step 4.02 implemented.
G.14	Who is **responsible for planning & scheduling** the work orders?		anyone else	each maintenance technician	a maintenance supervisor	a dedicated maintenance planner	4	Roles implemented as per FW sections 3 & 4
G.15	Is the **planning process** with all it´s necessary descriptions/procedures well known to all participants involved (different names of positions in use)? (Add 1 point for each participant)		production - maintenance coordinator	maintenance engineer	supervisor / foreman	planner	4	Overview training delivered to all roles, plus additional detailed training where required.
G.16	Which kind of **tools and aids** are used for planning and scheduling?		not at all, only paper for notes	register, card index, tables for planning, etc. / EDP service programs (eg. MS-Office)	CMMS with planning / scheduling capability	ERP-system with integrated CMMS and planning / scheduling capabiltiy	4	Integrated scheduling capability was implemented as a result of framework CMMS implementation specification.
G.17	Has **risk assessment** been developed for all routine planned maintenance activities? (e.g. Task risk analyses)	x	no assessment	only complex routine jobs are assessed	All routine planned maintenance activities are assessed.	All routine planned maintenance activities are assessed and re-evaluated after every job.	4	Framework step 3.04 implemented
G.18	Are **Risks evaluated** of work orders for all critical systems before planning and workpreparation?	x	no evaluation	only for complex jobs or by demand		Risk evaluation for all workorders , for all critical systems	4	Framework step 3.04 implemented
G.19	Are Permits, Lock-off/tag-off requirements specified in work orders and assosiated documentation?	x	No	only for complex jobs or by demand	Permits and LoTo requirements sepcified for every W.O.	Permits and LoTo requirements sepcified for every W.O. and re-evaluated after every job.	4	Framework step 3.06 implemented
G.20	Are work orders **time / cost estimated** before (decision of) execution (man hours, material and / or supporting services needed)?		no estimates	only for bigger jobs or by demand	all work orders are time estimated	all work orders are time and cost estimated	4	Framework steps 3.08 and 3.09 implemented
G.21	Work order planning includes ..... (Add 1 point for each of the following covered)		job plan (with tools required) and / or specific job instructions (safety)	duration	material required	resources (internal & external) required	4	Framework steps 3.06, 3.07, 3.08 and 3.09 implemented
G.22	Are **service catalogues / bill of materials/resources in use** for planning maintenance jobs?		no	sometimes for complementary trades / only for services from contractors (like piping, motor repairs, etc.)	for 40 - 60 % of jobs	for 60 % or more	4	100% due to implementation of framework steps 1.13, 3.09 and 3.10.
G.23	Short clarification and **coordination meetings** for work on critical systems between production and maintenance are held	x	no meetings / any other frequency longer as one week	weekly; on demand	twice per week	once to twice per day	4	Twice per day due to implementation of framework steps 2.07 and 4.19.
G.24	A maintenance and production **planning & coordination meeting (for approving weekly plan)** is held....		no meetings or any other frequency			weekly	4	Framework step 4.09 implemented with a weekly frequency
G.25	Are **maintenance/operations blue collar workers involved** in planning of work?		no	general		on demand for complex jobs	4	Framework step 3.04 implemented

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
27								
G	**Planning & Scheduling**		0 point	1 point	3 points	4 points	points	Remarks
G.26	Is **measuring of performance for planning** (with key performance indicators (KPIs)) in use (share of planned jobs, performance rate for work orders in the plan, etc)?		no		sometimes, for some jobs	general	4	Several [redacted] KPIs assess planning performance (e.g. planned/actual duration)
G.27	Percentage of planned work orders experiencing **delays due to poor or incomplete plans**		no planning / no measurement / more than 50 %	30 - 50 %	10 - 30 %	less than 10 %	4	2.8% in the month of Jan 2018 (due to inadequate planned duration).
G.28	Maintenance **working plans / job schedules** are issued		any other frequency	daily	every 2 to 5 days	weekly	1	Framework step 4.14 implemented (daily) *
G.29	Are **projects & modifications** also included in the working plans?		no working plans	only bigger projects and maintenance activities	only maintenance activities	complete, all activities are included	4	Framework step 6.06 implemented
G.30	How big is the **backlog of maintenance work** (without jobs for the next shut down / turnaround)?	x	not known; not recorded; less than 1 week; more than 8 weeks	1 - 2 weeks	4 - 8 weeks	2 - 4 weeks	4	2.04 weeks as of 09/02/2018**
G.31	The **backlog of maintenance work** is available by…. (Add 1 point for each category)	x	date needed by	executing work shop / trade group	Critical equipment	resources / workforce required	4	Framework step 2.20 implemented
G.32	Is a percentage known for maintenance involvement in **non maintenance related** tasks.		Not known.			Non maintenance related tasks are tracked	4	Admin tasks are tracked on the schedule via a dedicated "unavailable resource" type

*The rating criteria for this question contradicts the findings of this research - i.e. that in highly reactive contexts, a daily frequency is the most appropriate choice.

**163 hours of non-routine work as of 09/02/2018, with 10 maintenance technicians working 8 hour days @ 20% schedule availability for non-routine tasks (as per implementation of framework step 4.06)
= 2.04 weeks

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
14								
M	**Recording *)**		0 point	1 point	3 points	4 points	points	Remarks
M.1	Is it described how **completion of work orders** shall be performed?	x	no instructions	written instructions, sometimes followed	written instructions, mostly followed	detailed procedure, generally followed	4	This is the intent of framework section 5
M.2	What percent of total jobs for critical systems performed by maintenance are **covered by written work orders**?	x	< 59 %	59 - 94 %	95 % and more	All	4	100% - this is the intent of FW sections 2 and 5 Framework step 2.25 implemented, option A
M.3	What percent of maintenance **man-hours are recorded to a work order**?		less than 25 %	25 - 59 %	59 - 94 %	95 % and more	4	100% - mandatory field
M.4	Is there a **registration of actual working hours** spent on each work order by.....?		information is not recorded	anyone else	the supervisor of the group	the technician performing the work or dedicated person	4	Optional framework step 5.30 implemented
M.5	The **registration of actual working hours** spent on each work order is done ....?		information is not recorded	at the end of the month	weekly	daily	4	At the end of the task or working day
M.6	Are required **material and used spare parts** registered on each work order by .....?		information is not recorded	anyone else	the supervisor of the group	the technician performing the work or dedicated person	4	Framework step 5.32 implemented
M.7	Is there a system with **failure codes (types, causes)** established and how is it used?	x	no	yes, but not or only sporadic in use	yes, mostly in use	yes, required field when data input	4	Mandatory field - FW step 5.40 implemented
M.8	Is there a **final registration of causes** (fault codes), why the job was executed, by....?	x	information is not recorded	anyone else	the technician performing the work	the supervisor of the group	3	Framework step 5.40 implemented*
M.9	Are the **codes** understood as appropriate?	x	no codes	few code without or only few information value	clear definitions / too many codes, and in use	appropriate number of codes, well defined, and in use	4	Recently reviewed during CMMS upgrade to consolidate and streamline code options
M.10	1 Add 1 point for each of the **categories which are tracked** by work orders		failure codes	actual down time	actual materials & spare parts	actual craft hours (internal, external)	4	FW steps 5.30, 5.32, and 5.40 implemented
M.11	The **work order history** is accurate in tracking clearly identified causes of failures in x % of the asset´s history	x	less than 40 %	40 - 64 %	65 - 94 %	95 % or more	4	100% - framework implemented prior to the beginning of TMF's operating life
M.12	Is there a **written long text** for historical use?	x	less than 40 %	40 - 64 %	65 - 94 %	95 % or more	4	Optional framework step 5.35 implemented
M.13	Is there a requirement for (minumum) **registration before completion of a work order** and is it followed?	x	no instructions	written instructions, sometimes followed	written instruction, mostly followed	generally followed	4	Framework step 5.06 implemented
M.14	Is plant **configuration control** part of this requirement?	x	no			yes	4	PTW system controls temporary plant changes
M.15	What percent of work orders are **closed** (technical, commercial) **within six weeks after finalising the job**?		less than 25 %	25 - 59 %	60 - 94 %	95 % or more	4	Technical completion weekly Commercial completion monthly
M.16	Is the **quality of workorder** defined and measured (completeness, e.g. priority, tag code, SMART description, root cause indicated, etc.)	x	No definition and measurement	A definition is described		A definition is described and quality workorders are recorded	4	Completeness monitored via specific KPIs, as per implementation of framework step 6.04
M.17	1 Are relevant **KPI's defined** to track the work order quality and process?		% planned work according to week plan	% Back log	% breakdown workorders and reason for deviate from planning	% work order ready before every job task.	4	WO planning quality monitored via several KPIs, as per implementation of FW step 6.04

*The rating criteria for this question contradicts the findings of this research - i.e. that fault code data is more accurate and informative if entered by the technician who executed the task, rather than their supervisor.

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
18								
N	**Analysis, Reporting & Communication**		0 point	1 point	3 points	4 points	points	Remarks
N.1	Is there a **structured procedure** for analysis and reporting?	x	no instructions	written instructions, sometimes followed	written instructions, mostly followed	detailed procedure, generally followed	4	This is the intent of framework section 6
N.2	Is there a defined **"tool-box"** with methods for analysis in the company (like "why tree", fishbone, Pareto, RCA, etc.)?	x	no		no toolbox, but knowledge of some tools	yes and is regularly in use	4	Framework step 6.02 implemented
N.3	Are there resources available in the (maintanance/operations) organisation to **perform analysis and reports** regarding the maintenance/operations activities and plant performance?		no resources	person(s) with limited knowledge and / or availability	person(s) with good knowledge and / or availability	trained and dedicated person(s), who make analysis systematically and reports regularly	4	Framework steps 6.02 and 6.05 implemented
N.4	What percent of the work orders are **available for historical data analysis**? + historian function (plant data)	x	less than 25 %	25 - 59 %	60 - 94 %	95 % and more	4	100% - framework implemented prior to the beginning of [redacted] operating life
N.5	Can the recorded **input data** (eg. failure codes, used material, etc.) be used for **creating key figures / KPIs** for analysis, interpretation, etc.?	x	not useable, no data feedback	poor	quite good	complete	4	Framework step 6.03 implemented
N.6	Are **relevant KPIs** defined and used? *) *(for monitoring availability, effectivity, planning, cost, organisation, configuration)*	x	no KPIs	some KPIs are defined, but not practicable	KPIs are defined, but not complete to measure the maintenance process	KPIs are defined and used, with clear informative value	4	Framework step 6.04 implemented. KPIs defined, generated and reported monthly.
N.7	Are **statistics of agreed KPIs** reported on a regular basis?		no reports of KPIs	quarterly reports or longer frequencies	frequency of reports between one and three months	monthly reports, continuously updated	4	As above
N.8	Are those KPIs used for **active management** of the maintenance/operational activities?	x	no KPIs	KPIs have no / very limited influence on maintenance management	KPIs have sometimes influence on maintenance management	KPIs are used systematically on maintenance management	4	This is the primary intent of FW section 6.
N.9	Is there a **reporting regarding actual (critical) maintenance/operations activities**?	x	no written reports	written reports are made sometimes	written reports for critical and important maintenance activities	there is a regular structured written report regarding maintenance activities	4	Framework step 5.01 implemented
N.10	1 Are there **reports** of .... (Add 1 point for each category)		(Top 10 of) HSE incident causes	(Top 10 of) down time causes	(Top 10 of) equipment down times (in hours, lost cost)	(Top 10 of) actual maintenance cost on equipment level	4	Framework step 6.04 implemented with all listed measures included.
N.11	1 Are there also **reports** of .... (Add 1 point for each category)		planning & scheduling (like estimated cost / actual cost, scheduled hours / worked hours, etc.)	purchasing & inventory performance (promised versus actual delivery dates, quoted versus actual prices, stock outs, level of services, turnover rate, etc.)	maintenance controlling (monthly maintenance costs versus budget, labor and material costs as percentage of total costs, maintenance cost per unit of production, etc.)	systematic improvements (no. of implemented improvement, documented effects, fullfillment rate of planned activities, etc.)	3	Inventory management performance measures are not available (outside of framework scope)
N.12	Are there **special reports made** - eg. after overhauls or plant improvement?		there are no special reports made	special reports are made sometimes		special reports after overhauls and plant improvements are regular made	4	The same reports are used during a STO, but grouped by STO identifier field
N.13	How is the **communication** regarding the contents of the reports?		there is no reporting	the information exchange is insufficient; no copies are distributed	only a small group of persons is informed about the contents of the reports	systematic information of other departments about the contents of the reports	4	Distributed to all relevant stakeholders, as per implementation of framework step 6.05
N.14	1 Is there a **distribution list** for different reports? (Add 1 point for each category)		notice boards, flat screens	maintenance engineers & planners	maintenance supervisors / foremen	management group	4	Distribution includes all those listed

Nr.	Elements		Rating criteria I	Rating criteria II	Rating criteria III	Rating criteria IV	Rating	Remarks
18								
N	**Analysis, Reporting & Communication**		0 point	1 point	3 points	4 points	points	Remarks
N.15	Are **regular reports communicated** locally in the maintenance/operations organisation?		no internal meetings / no reports	sporadic meetings / only supervisor / foremen are informed about relevant contents	regular meetings / maintenance/operations management, supervisor, foremen are informed about relevant contents	systematic information of the whole maintenance/operations staff by information boards and supervisor / foremen	4	All maintenance / operations staff are informed (not difficult in a small organisation).
N.16	How is **communication between maintenance and production** organized?	x	there is nearly no communication between maintenance and production	there are some meeting where problems are discussed	there are regular meetings with not fixed participants	there are regular meetings with a structured procedure and fixed participants	4	Various framework steps include regular structured meetings with Ops.
N.17	Is there a **systematic discussion** (between **production & maintenance**) of the reports done?	x	no meetings / no discussion of the contents		contents are discussed (sometimes, sporadic) with a small group of persons	regular meetings (minimum monthly), where statistics and trends are evaluated and work (to be done further on) is prioritised	4	Framework step 6.05 implemented
N.18	What is the **atmosphere** during this communication?	x	there are generally a lot of conflicts		depends on the topic and on the participants	in general objective, target oriented and in a good mood	4	Strong continuous improvement culture at [redacted]

Nr.	Elements		Rating criteria I	II	III	IV	Rating	Remarks
14								
P	**Systematic Improvement & New Technology**		0 point	1 point	3 points	4 points	points	
P.1	Is there a **procedure describing systematic improvement** and is this well known in the organisation?		no procedure	existing procedure but not known in the organisation	existing procedure well known in the organisation, sporadic used	existing procedure well known and used in the organisation	4	This is the purpose of framework section 6.
P.2	**Systematic improvements** shall contribute to achieve the long term goals within ..... (Add 1 point for each category)		up-time of equipment	maintenance cost	HSE	product quality	4	These goals directly match [redacted] AMS goals and are built into the WO Request improvement categories (i.e. FW step 6.06).
P.3	Are **procedures** (regarding risk evaluation, goals, quality, release, etc.) available for carrying out **plant/system modifications**?	x	no procedure	existing procedure but not known in the organisation	existing procedure, known but not always followed	existing procedure well known and used in the organisation	4	Plant modification procedure available. Limited use at present due to new facility.
P.4	Is there a procedure for carrying out **"small types of improvement"**?		no procedure	existing procedure but not known in the organisation	no procedure but improvements are done	existing procedure well known and used in the organisation	4	Framework section 6 implemented. Appropriate for small and large improvements.
P.5	**Improvement activities** for the (production) equipment and utilities are done......		never		not systematically but selectively / punctually	systematically and regularly	4	Framework section 6 implemented with routine meetings to drive improvement.
P.6	Is there proof of an **active system** for plant improvement plans and activities	x	no active system	System available but not much activity and progress		Active system for plant improvements available and lived by the organisation	4	Improvement system managed and recorded via the CMMS as per FW section 6.
P.7	Is there a **budget** forseen for systematic improvements?		no budget	some / not sufficient budget	sufficient budget, not calculated	calculated & sufficient budget	4	Core part of operational budget
P.8	Are results of analysis (e.g. of failure codes, time delays, down times, etc.) used for **systematic improvement** activities?		no analysis done; not used as input	sometimes base for improvement activities		based on analysis there are regularly improvement activities	4	Framework steps 6.01 and 6.02 implemented.
P.9	Which **knowledge** is used for plant improvements?		there are no plant improvements	knowledge of the plant supplier	knowledge of production or maintenance	knowledge of production and maintenance	4	FW steps 6.05 and 6.07 involve both parties.
P.10	Are **profitabilty calculations** part of improvement activities for production equipment and utilities?		no profitability calcutlations	calculations in some cases		calculation for every case	4	Framework step 6.06 implemented.
P.11	Is there a **follow-up measurement** of completed improvements / modifications (with measurement and registration of achieved (cost) effects)?	x	no follow up measurements	in some cases, for improvements with high benefit		financial effects are regularly identified and analysed	4	Framework step 6.09 implemented.
P.12	Is it defined **which person** is responsible for initiating improvement work?		no resources	different, not defined persons		defined person(s)	4	Defined within specific Improvement WO field as per FW step 6.08
P.13	Is personnel from both **operation and maintenance** involved in the improvement work?		no resources	from case to case		general	4	Where appropriate depending on the nature of the improvement
P.14	Is there a **visible support of (general) management** for systematic and continuous improvement efforts?		no support	weak support	moderate support	strong support	4	Core part of [redacted] company values and strategy
P.15	Does the (management of) production / operations take an **active role in initiating** and deciding improvement work?		no support	weak support	moderate support	strong support	4	Framework step 6.07 implemented Ops management are key stakeholders.
P.16	Are improvements on the **agenda of regular meetings** between production / operations and maintenance?		no relevant meetings	sometimes discussed		regular meetings, one of main topics	4	Framework steps 6.05 and 6.07 implemented