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A Robust Design for Lifecycle Cost with Reliability Analysis Integration

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Abstract

Maintenance, repair, and overhaul (MRO) is the most significant cost driver over a complex engineering asset lifecycle. Therefore, high-value manufacturers are required to plan MRO occurrences to optimize the overhaul cost while achieving the desired performance. This trade-off imposes a shift towards a proactive maintenance strategy. However, creating a long-term proactive maintenance plan is challenging due to uncertainties in the performance of the asset and its critical components. Hence, this paper presents a robust design framework for the lifecycle cost estimation process by integrating reliability life data analysis. The level of data availability across the lifecycle is considered. The framework is proposed based on a literature review and the Delphi method. This study highlights that the level of robustness in the lifecycle cost estimates can be achieved by continuous feedback to the design phase and to the body of knowledge over the asset lifecycle. Moreover, this study suggests that the optimization model for the trade-off between cost and reliability should fulfil safety and environmental sustainability requirements when providing a cost-effective reliability solution.

Keywords: Reliability, Lifecycle cost; Life data analysis; Proactive maintenance, MRO

1. Introduction

Complex engineering assets refer to high-value equipment with a long lifespan. These two characteristics in equipment necessitate high-value manufacturers to provide robust long-term cost estimates over the entire lifecycle. Through-life or lifecycle costing (LCC) refers to the cost estimation from acquisition, through use and maintenance, to end-of-life. The existing asset management and lifecycle cost modelling frameworks, such as product lifecycle management, CADMID cycles [1], PAS-280 framework [2], and SSCM [3], identify the lifecycle phases and the associated cost drivers over an equipment lifecycle. It is important to note that the level of uncertainty in the cost estimations over the use and maintenance phase is relatively high. This is mainly due to the complications in maintenance planning and estimating the time between overhauls (TBO) for complex engineering assets. This uncertainty causes one of the main challenges in estimating LCC for high-value assets over the operation.

There are several techniques to assist with increasing the level of accuracy in estimating TBO and improving the robustness in proactive maintenance planning for complex engineering assets. Accuracy in the estimation of remaining useful life (RUL) for critical components, sub-systems and systems in the equipment is crucial for TBO estimation. Analysing life data, time-to-failure data, or threshold data are the most common approaches to estimating the probability of failure and RUL. In addition, reliability life data analysis (LDA) using Weibull, exponential or log-normal distributions are the most popular approach for estimating TBO for complex engineering assets. In a recent study by Zhou et al. [4], Copula distribution is also introduced as an effective approach for TBO estimation based on flying hours and cycles in the aerospace industry.

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Over the past decades, reliability centered maintenance (RCM) has provided an optimisation framework for maintenance planning using failure mode and effects analysis (FMEA) at the component level. Moreover, integration of reliability block diagram (RBD) and fault tree analysis (FTA) with LDA and RCM are well-established methods that enable reliability analyses from asset level to component level and the other way round.

Reliability, availability, maintainability, quality, and safety are the most critical measures when optimising LCC. Reliability can be defined as the quality of performing consistently at the desired level for a specific period. Therefore, measures such as availability (as the quality of being able to be used), and maintainability (as the quality of being able to be maintained) are inherent in reliability. Safety measure is not a quality for equipment but a condition that should be fulfilled when designing the equipment and the associated services. A trade-off between cost and reliability should guarantee maximum safety requirements and cost-effective reliability. The design of equipment and services at the early stages directly impacts safety. Several frameworks, such as design for safety, design for manufacture and assembly, and design review based on failure modes, exist to provide insight into design requirements. It is worth noting that, with the NetZero target by 2050, the high-value industry also intends to consider environmental sustainability metrics. Therefore, the sustainability requirements should be fulfilled within the optimisation model.

This research aims to study the integration between reliability and lifecycle cost estimation process considering the existing methods and frameworks in reliability and LCC. Moreover, this research investigates the existing design frameworks at the manufacture, in-service, and ‘end-of-life’ phases to assess the level of robustness in lifecycle cost estimates at the early design stage. The remainder of this paper is as follows: relevant literature on reliability life data analysis and lifecycle cost estimation are reviewed in Section 2. A robust design for lifecycle cost considering LDA at the early stage is proposed in Section 3. The proposed design is conceptualised and discussed in Section 4. Finally, the highlights from this research and the concluding remarks are summarised in Section 5.

Nomenclature

CADMID	Concept, Assessment, Design, Manufacture, In-service, Disposal
DFS	Design for Safety
DFMA	Design for Manufacture and Assembly
DRBFM	Design Review Based on Failure Modes
FMECA	Failure Mode, Effect and Criticality Analysis
FTA	Fault Tree Analysis
LDA	Life Data Analysis
MTBF	Meantime Between Failure
MTTR	Meantime to Repair
RBD	Reliability Block Diagram,
RUL	Remaining Useful Life
SSCM	Super Simple Cost Model
TBO	Time Between Overhauls
TTF	Time to Failure

2. State-of-the-art

This research focuses on the integration of reliability and lifecycle cost estimation for high-value assets. A broad research stream of ‘TITLE-ABS-KEY (reliability AND “life data” AND cost)’ is selected using Scopus and Google Scholar as the research repositories to study the existing knowledge.

Reliability Centered Maintenance (RCM) originated in the airline industry in the 1960’s to minimise maintenance costs by promoting proactive strategies in order to maintain the desired level of performance for high-value assets. Since then, there have been enormous studies around RCM to optimise maintenance planning and, more importantly, to estimate the time-to-major overhauls more accurately. Since Mid-80’s, studies have been investigating the integration between RCM and lifecycle cost (LCC). Despite the genuine concept of LCC as the total cost from creation to end-of-life, existing literature mainly focused on the ‘in-service’ phase and the cost of overhaul estimation. Jambulingam and Jardine [5] highlighted the importance of RCM and the necessity of failure analysis in minimising the maintenance cost. Wen [6] raised the importance of uncertainty assessment as a trade-off between reliability and the expected lifecycle cost. Andrawus et al. [7] proposed a ‘modelling system failure technique’ as an effective quantitative approach to study the failure analysis at the system level. Kleyner and Sandborn [8] highlighted the importance of validation plans and warranty return cost in the trade-off between lifecycle cost and reliability. The literature emphasises system redundancy strategies and system reliability in lifecycle cost optimisation [9,10]. The concept of ‘family item’ is introduced by Macchi et al. [11] as an additional classification for critical components into operation conditions and technological properties. This latter study suggested that this classification can be considered to optimise the reliability analysis process.

Maintenance planning and optimisation have been studied tremendously by authors over the past decades. Investigating the optimal maintenance strategies has been learned from a trade-off between corrective and preventive maintenance on the one hand, and time-based preventive and condition-based preventive on the other. Tee et al. [12] study suggested that minimal lifecycle cost should be achieved by prioritising maintenance strategies based on operational reliability and failure severity. Elmahdy [13] conducted a comprehensive study on different statistical methods to estimate the Weibull distribution parameters over the bathtub hazard model. This study analysed Goodness-of-Fit to determine the best method for modeling life data. The literature also highlighted the importance of operational reliability analysis insight into components’ design [14] and warranty policy assessment [8,15].

Extended inverse Weibull distribution using Marshall–Olkin method is introduced in Okasha et al. [10] study as an effective approach for reliability life data analysis. The impact of multiple dependent degradation processes in LDA and LLC is studied by Liu et al. [16]. The authors proposed a modelling system reliability analysis using the copula distribution function. In a more recent study, a data-driven approach using wavelet packets decomposition and bidirectional long-short-term memory is proposed to predict critical components' degradation process and RUL [17]. Jana and Bear [18] proposed an estimation technique to evaluate the parameters of inverse Weibull distribution for multi-component stress-strength systems. The authors argued that based on the availability of data on either scale or shape function, different techniques in Bayes estimators could be implemented.

Over the literature search, it is observed that the relevant studies on reliability informed LCC are sparse. The literature mostly focuses on the assets' 'in-service' phase and the impact of reliability life data analysis (LDA) on condition-based maintenance improvement. This study contributes to the existing knowledge by taking a step forward to study the impact of LDA on lifecycle cost from the cradle to the grave. With that note, the feedback from components' life data during the manufacture, in-service, and 'end-of-life' phases into the early stage 'design phase' are investigated. In this study, the robustness of cost model design refers to the steadiness in lifecycle cost estimates at the early stages.

3. Robust Design for Lifecycle Cost

A robust design for lifecycle cost is proposed based on the literature review and a semi-structured Delphi method with academic experts in cost, maintenance, inspection, and data analytics topics. The proposed design framework comprises five main stages: data collection and processing, reliability model, reliability-informed cost, lifecycle cost model and reliability-cost trade-off. In addition, four main phases of design, manufacture, in-service and end-of-life are considered for the equipment lifecycle. The proposed framework is presented in Figure 1.

Stage 1 – Data Collection and Processing: for high-value equipment, several databases over its lifecycle can be considered as input to reliability modelling and analysis. At the early design stage, the reliability requirement, operation and use conditions are key. The design for reliability (DfR) framework is an effective tool for analysing and controlling reliability. Several analyses can be implemented, such as stress-strength, static and dynamic finite element simulation, fault-tree analysis and reliability block diagram [19]. At the 'manufacture' phase, some key reliability data are from accelerated life testing, test-to-failure, reliability growth testing, environmental stress screening, etc. Over the 'in-service' phase, lifetime, run-to-failure, threshold, logbook, FMECA, FRACAS (failure reporting analysis and corrective action system), and sentencing process, are some primary databases. Finally, at the 'end-of-life' phase, evaluating the reliability index (including availability, failure rate, time-to-repair, time-to-overhaul, and inspection interval), efficiency and effectiveness of maintenance interventions are crucial [20].

Stage 2 – Reliability Model: at this stage, four main steps are designed (1) data processing, (2) reliability analysis, (3) hazard model and (4) reliability metrics. The key methods and tools at each step are introduced and categorised in terms of the level of data availability. Three scenarios of complete data, censored data and no data are considered. In step 1, the distribution fit can be selected for data processing using Weibull, log-normal, exponential, cupola, etc. distributions. Moreover, the goodness of fit analysis (GOF) for best-fit distribution can be implemented for censored data. At this stage, some data in text and image formats should be initially processed using several text mining and image mining and processing techniques. In step 2, the Median Ranks method, linear regression analysis, maximum likelihood estimation and Generative adversarial networks are some of the possible options for reliability analysis for complete and censored data. Moreover, other techniques, such as analogy analysis and expert-based reliability knowledge, are applicable when no data is available. In stage 3, Mean Rank and 'mean residual life' methods can be implemented to evaluate the probability of failure occurrences and their distribution over time (i.e. bathtub curve hazard function). Regardless of the level of data availability, Survival analysis is an effective approach for evaluating the hazard function. Finally, in step 4, key reliability metrics such as MTBF, MTTR, TBO, TTF and RUL can be projected. Reliability can be calculated in a generic format, as in Equation 1:

$$R(t) = e^{-\lambda t}, \tag{1}$$

where, $R(t)$, is the reliability of a critical component over time and λ, is its failure rate, which is equal to the $1/MTBF$. The reliability of a system can be calculated using RBD and based on the redundancy design. The failure rate can be evaluated based on the selected distribution fit for each critical component.

Stage 3 – Reliability-informed cost: at this stage, the proposed framework recommends the list of reliability-related measures to be considered at each lifecycle phase to optimise the cost. For instance, at the 'design' phase, the measures can be the target reliability, material selection, and redundancy design parameters. At the 'manufacture' phase, the components' life expectations and the manufacturing quality control parameters can be considered. Reliability analysis feedback is crucial at the 'in-service' phase. Measures such as sentencing, predictive and proactive maintenance planning, repair and reject limits and inspection intervals are key to influencing cost. Finally, at the 'end-of-life' phase, the reliability analysis outcome can mainly influence evaluating the cost of re-purpose or retrofitting in case there is still an operational need for the equipment.

Stage 4 – Lifecycle Cost Model: lifecycle costing at the early design stage is mainly based on historical data, expert knowledge, and analogy methods. According to the previous study by the authors [3] and based on the existing LCC and CADMID frameworks, the generic model for LCC of an item can be defined as in Equation 2:

$$LCC = C_1 + C_2 + C_3 + C_4, \tag{2}$$

where, C_1, is the total cost of concept and design and, C_2, is the cost of manufacturing. The total cost of C_1+C_2, can be described as the 'price of use' for an item, including procurement (or production), assembly, installation, and transport. C_3, is the in-service cost. C_3 includes the cost of inspection, standby support, health monitoring, investigation, reactive (on-wing) maintenance, downtime, refurbishment, and overhaul of the equipment. The cost of the overhaul includes the cost of transport testing, maintenance, repair, replacement, and other work scope activities at the overhaul. The cost of downtime includes the cost of disruption and lost opportunity. The cost can be caused by unexpected failure and the penalty cost due to the lack of guaranteed performance, capability, and reputation. The lack of safety conditions and environmental issues can also cause downtime costs. It is worth noting that the in-service cost, C_3, has other indirect cost drivers, such as taxes, warehousing, inventory, obsolescence, etc. Finally, C_4, is the cost of end-of-life. The cost can include the cost of disposal, retrofit, re-purpose, recycling, transport, etc., according to the end-of-life scenarios for the equipment and based on the product and service contracts.

Stage 5 – Reliability-Cost trade-off: at this stage, the reliability measures which are identified from stage 3 can be considered to model optimisation. The optimisation model aims to create value for the industry by the trade-off between cost and reliability, and is subject to fulfilling safety and environmental sustainability requirements. The generic optimisation model can be therefore defined as in Equation 3:

$$\begin{cases} min_{\boldsymbol{X}} = F(\boldsymbol{X}) = \left(f_C(\boldsymbol{X}), 1/f_R(\boldsymbol{X})\right), \\ s.t. \qquad g(\boldsymbol{X}) \in \boldsymbol{dom\ G} \text{ and } h(\boldsymbol{X}) \in \boldsymbol{dom\ H} \end{cases} \tag{3}$$

where, $\mathrm{f_C}(\mathbf{X})$ and $1/\mathrm{f_R}(\mathbf{X})$ are the optimisation objectives for cost and reliability, respectively. $\mathbf{X}$ is the decision vector, including the selected reliability measures from stage 4. The optimisation function, $\mathrm{F}(\mathbf{X})$, subject to fulfilment of sustainability function $\mathrm{g}(\mathbf{X})$, and safety function $\mathrm{h}(\mathbf{X})$, staying within sustainability, $\boldsymbol{G}$, and safety, $\boldsymbol{H}$, requirements' domain.

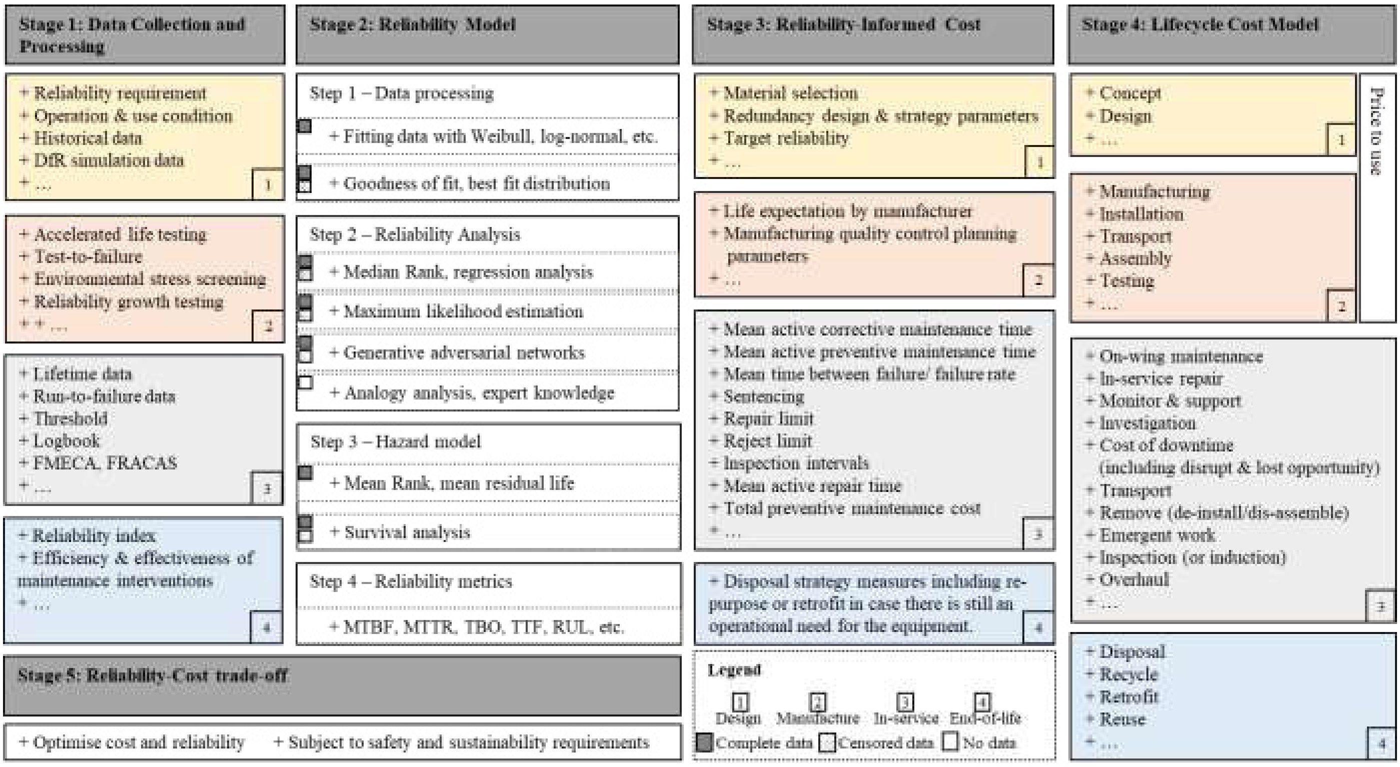

Figure 1: Robust design framework for lifecycle cost model with reliability analysis integration

Robustness in the proposed framework (see Figure 1) can be gradually achieved over the lifecycle by improving the accuracy of cost estimates at the early design stages. Improving the level of accuracy and confidence in LCC model requires continuous feedback in two ways, feedback to design and to the body of knowledge. Feedback to design is the feedback from lifecycle phases (i.e. manufacture, in-service and end-of-life) to the 'design' phase in terms of reliability metrics (from stage 3) and reliability-informed cost measures (from stage 4). Feedback to the body of knowledge is feedback from stage 5 (optimal solutions for reliability measures) to stage 1 (data collection). The feedback loops among different framework stages across the lifecycle phases are presented in Figure 2. These two feedback loops enhance the knowledge at the early design stage and, therefore, the level of robustness in lifecycle cost estimates.

Feedback to design: the feedback from the 'manufacture' phase to design is possible through DfMA (Design for Manufacture and Assembly). DfMA is one of the design frameworks to enhance the ease of manufacturing processes and assembly procedures. This framework is a proven technique in product design to optimise assembly and test accuracy, manufacturability and reliability at lower costs [21]. At the 'in-service' phase, the Design review based on failure mode (DRBFM) framework together with FMEA and RCM can be considered for enabling feedback to design. DRBFM considers both equipment structure hierarchy and design change management structure to recommend updates and modifications to design [22]. Additionally, DRBFM applies a systematic approach to identify the potential failure root causes and the associated risks. At the 'end-of-life' phase, there are limited research investigating specific framework and techniques to feedback to design. However, the well-known lifecycle analysis framework (LCA) can be implemented to capture lessons learnt at the end-of-life stage and evaluate maintenance strategies' efficiency and effectiveness over the product in-service time. One of the key steps in LCA is to understand how failures occur over time and to define failure rate, reliability, availability, and MTTF to estimate best the optimal inspections and maintenance intervals [20].

As mentioned previously, DfR is the process of designing reliability into products and a science-based method to ensure reliability. DfR should be integrated into the lifecycle phases to provide reliability metrics at the early design stage [19].

Feedback to the body of knowledge: this is to ensure continuous improvement in optimal solutions at stage 5. The insights and knowledge on optimal reliability and cost measures should be fed back to the relevant knowledge base and databases at stage 1.

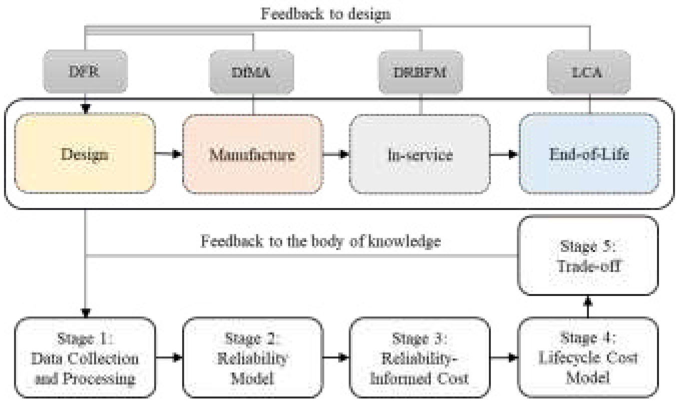

Figure 2: Feedback loops for the robustness of the proposed framework

4. Discussion

There are several reliability tools and frameworks available within the industry. FMEA (or FMECA) has perhaps the most popular applications. FMEA is the basis for RCM process to design proactive maintenance planning and support strategies for non-maintenance solutions. However, implementing a complete RCM process, especially regarding the non-maintenance solutions, is challenging. The solutions that require feedback to design e.g. equipment re-design, modified operating procedures, updates on training, supply chain modification and updates, require a trade-off between LCC and reliability. This compromise is massively based on expert knowledge in the current climate, which requires further research.

This study investigated the link between life data analysis and lifecycle cost estimation and presented a robust design framework with reliability analysis integration within the lifecycle cost model. The proposed framework is composed of five main stages from data capturing to reliability-cost trade-off analysis over an equipment lifecycle. The framework aims to present a robust design outline for the integration between reliability and lifecycle cost estimation process with a view to enable trade-off between LCC and reliability. In stage 1 of the framework, the relevant databases are identified across the lifecycle based on the existing knowledge. These data can be a combination of numeric, text and images from several sources such as logbooks, sensors, non-destructive testing, etc. These data will be then processed at the next stage to be later used for the reliability model development. In stage 2, several approaches to reliability analysis of life data for a different level of data availability are reviewed from the literature and considered in the proposed framework. Some life data distributions fitting such as Weibull modelling [5,13], Extended inverse Weibull [18,23], and Copula [4,24] are considered. In stage 3, the reliability-informed cost measures such as system redundancy [10], critical components' re-design, maintenance intervals [14], and inspection interval [12] are identified. In stage 4, the lifecycle cost model is conceptualised based on previous studies by [1,3,25]. And finally, in stage 5, the generic optimisation model is defined. At this stage, several optimisation algorithms, such as the Genetic Algorithm [10,12], Ant Colony Algorithm (ACA), and Swarm Optimization Algorithm (SOA), can be considered for reliability and LCC optimisation. The robustness of the framework is possible by investigating the feedback methods and enablers from reliability analyses to the early 'design' phase across the lifecycle. Several methods and frameworks, such as DfR, DfMA, DRBFM, and LCA are specified for this purpose.

The proposed design framework in Figure 1 and the feedback loop architecture in Figure 2 conceptualised the steps and processes required for robust reliability analysis and LCC integration over the equipment lifecycle. Further considerations should be put in place to enable the framework implementation within high-value manufacturing. A seamless approach is required to capture, process, and analyse data over the equipment lifecycle. Moreover, the proposed feedback loops should be designed across different stages and lifecycle phases to fulfil robustness in reliability-cost integration. Industries use several software, tools and platforms for data acquiring, storing, processing, modelling, and analysis. The integration between current and new platforms, standards and software should also be considered using appropriate information technology architecture and tool development frameworks.

5. Concluding remarks

A robust design framework for a lifecycle cost model with reliability analysis integration is proposed based on the literature review and Delphi method (see Figure 1). Existing literature in lifecycle costing, life data analysis and reliability analysis across different sectors such as aerospace [3], marine [5], construction [6], railway [11], manufacturing [14], and oil and gas [12] are reviewed. In addition, a semi-structured Delphi method with academic experts is completed. The robustness refers to the level of accuracy and steadiness in the cost estimates at the early design stage. In this paper, it is argued that such robustness can be achieved and gradually enhanced by providing continuous feedback to the 'design phase', and feedback to the body of knowledge at the data collection stage (see Figure 2). The proposed framework conceptualised based on the existing knowledge. Further study is required to test the validity of the framework. The proposed framework relevant to several practices such as early stage cost estimation, lifecycle management, bidding, maintenance planning and service design within the high-value industry. Moreover, the framework can support the industry at the commercial level for service provisions design [26] and engineering level to explore the application of emerging technologies such as digital twin [27] and automating cost estimation processes. Implementing the framework requires further consideration in providing the necessary infrastructure that enables seamless data capturing, processing and analyses over the equipment lifecycle. Further study should focus on the processes and requirement capturing for creating, designing, deploying, and supporting relevant software, tools, standards, and platforms.

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