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A design framework for technology prioritisation in the context of through-life engineering services

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Abstract

Lack of methods on standardising the prioritisation of technologies within the context of Through-life Engineering Services (TES) has been identified. Inspired by the TES value streams and support activity assets, existing within a common TES framework, a new design framework for technologies prioritisation is proposed. A dynamic toolkit to identify the most suitable technology is also developed, using a Quality Function Deployment method, Analytic Hierarchy Process and ROI analysis. A real case study from the defence sector is employed to validate the developed design framework and toolkit; the results show a well-structured guide that can effectively simplify the decision-making process.

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1. Introduction

In the past few years, Through-life Engineering Services (TES) have been gradually recognised as an important element to optimise the value and cost of major assets (e.g. complex engineered products, systems or systems-of-systems) [1]. Current research studies show that there is a wide spectrum of technologies enabling the delivery of TES. However, how to select the most effective and efficient technological solution for optimising complex assets in the TES context still remains a challenge [2]. Thus, industry has been struggling to make effective trade-offs to improve the decision-making process for technologies prioritisation due to obscure requirements and lack of reliable evidence. This, in turn, may lead to wrong decisions and, operational and financial risks. Additionally, from an academic perspective, despite the various applications existing in the literature associated with the TES concept, there has been limited research on standardising the prioritisation

process of technologies while providing a generic applicability. Therefore, it becomes essential to conduct research in order to develop a common framework for technologies prioritisation in the TES context to address the current demand.

Inspired by the TES value streams and support activity assets, existing within a common framework, this research study proposes a novel design framework for technologies prioritisation in the TES context to provide a well-structured guide for making informed decisions for major assets. The proposed framework explores four main points: (i) problems identification to understand the asset's requirements for technology solutions within the TES context; (ii) technology options review to converge the technology scope by ranking decision-makers' preferences; (iii) prioritisation of the reviewed technologies in view of engineering support activity assets; and (iv) technology prioritisation based on return on investment (ROI) analysis involving estimations on support activity assets and total discounted annual cost and savings.

Following the logic of the proposed framework, a dynamic Excel-based toolkit is also developed, enabling users to efficiently evaluate technology decisions in practice.

The remainder of the paper is structured as: *Section 2* discusses the literature review and identifies research gaps and contributions of this paper, *Section 3* presents the proposed design framework, in *Section 4* the proposed toolkit is developed, *Section 5* validates the proposed framework and toolkit through a case study from the defence sector, and *Section 6* provides a conclusion to the paper.

2. Literature review

In this section, the concept of a common TES framework is initially introduced. Steps and methods previously employed in the literature for the process of technology prioritisation are then identified, providing guidelines for this work. Finally, research gaps and contributions of this research are discussed.

2.1. Through-life Engineering Services (TES) Framework

The primary emergence of TES was as a product support application for helping organisations to achieve the highest availability and lowest cost throughout the whole life-cycle [3]. The definition was further elaborated as an integration of solutions for asset optimisation and technology evolutions [1]. With regard to the TES scope, a blend of engineering and technical decisions is captured [2]. In order to provide guidance to industry on how to improve the capability and productivity of major assets across the full supply, operate and support chain, a common framework of TES is proposed in PAS 280:2018 [1]. The framework identifies four value streams, namely *avoid*, *contain*, *recover* and *convert*, which can address the impacts of major asset deterioration in use and optimise their value and cost. *Avoid* targets reduce the amount of deterioration incurred; *contain* is applied to minimise the impacts of deterioration through inspection and maintenance timing and scope decisions; *recover* is the physical execution of inspection; and *convert* can capture, analyse and apply the learning experience from the other three streams to identify incremental improvements in value or costs.

2.2. Technology Prioritisation

Reviewing research works that focus on the process of technology prioritisation shows that there is a gap in the technology selection process across different industries. It is also observed that the majority of strategies considering the TES concept focuses on a specific domain or application rather than providing a generic applicability [2]. However, according to Table 1 that summarises the steps followed in [4–6] for technologies prioritisation, it is found that two key points should be addressed: (i) the scope for technology decisions, i.e. the identification of requirements of a given problem, as discussed in section 2.3; and (ii) the criteria for technology prioritisation, as discussed in section 2.4. Therefore, this work will prioritise technologies starting from these two points.

Table 1. Review of the Technology Prioritisation Processes.

Step	Reference [4]	Reference [5]	Reference [6]
1	Identification and Categorisation	Identification and Monitoring	Develop Market Requirements
2	Criteria Combinations Analysis	Selection and Approval	Determine Implications on Products
3	Technology Ranking Selection	Development Research	Technology Roadmap
4	Sensitivity Analysis	Acquisition and Adoption	Technology Prioritisation
5	—	Exploitation and Review	—

2.3. Methods for Requirements Analysis

Three methods have been selected for analysing this demand. Quality Function Deployment (QFD), developed in a matrix form, enables great comprehension of problem requirements through a translation from customer desires to technical language [7–8]. This method is can accelerate the process of R&D [8] and bring considerable cost reductions [7]. It has been widely applied in technology development, design and manufacturing fields [9]. Compared with QFD method, Theory and Innovative Problem Solving (TRIZ), providing a systematic process, is more rigid and arduous to interpret an optimum engineering application due to its variety of approaches [10]. Meanwhile, Failure Mode and Effects Analysis (FMEA), which functions as a quality tool to explore potential failures and consequences [11], may suffer lack of accuracy because of the loss of judgment integrity and limitations on ranking severity [12]. Hence, this research study selected the QFD for the requirements identification due to the benefits against the other reviewed methods.

2.4. Methods for Multi-Criteria Decision-Making

During the technology prioritisation process, multiple metrics-based evaluation promotes the multi-criteria decision-making (MCDM) methods. By comparing three methods including Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Multi-Objective Optimization on the basis of Ratio Analysis (MOORA), the AHP method has been selected, due to the following benefits:

- AHP demonstrates superiority on reliability and judgments objectivity, while providing mathematical flexibility and decreasing the effect of subjective alternatives [13]. During the consistency verification of AHP, pairwise comparison matrices act as critical feedback for decision review.
- AHP is a mature MCDM method to accumulate huge amount of empirical data and solutions for engineering problems [14]. This increases the transparency of prioritisation processes along with expansibility of experiences. Thus, decisions may reflect real situations [15].
- AHP provides a semi-automatic procedure for selection and scalability, reducing time and development costs [16].

Considering the other reviewed methods, TOPSIS requires abundant numeric values [7], while MOORA provides less transparency. Thus, AHP was adopted in this work.

2.5. Research Gaps & Contributions

The research gaps identified from the existing literature are: (i) few research studies explore the topic of technology prioritisation within the TES context. By extension, there is lack of research providing a step-by-step guidance on how to identify requirements and select criteria for prioritising technologies in the TES context. (ii) Limited work on developing a comprehensive technology selection process that can be applied to problems of different nature and further modified according to customer preferences. (iii) Lack of research studies that consider both engineering and financial aspects for TES technology decision-making.

The main contributions of this research work are: (i) designing a novel framework following a systematic process to achieve technology prioritisation in the TES context and developing a dynamic Excel-based toolkit that enables users to practically evaluate technology decisions; (ii) the proposed framework provides general applicability without focusing on specific problem areas; and (iii) engineering (AHP) and financial (ROI) aspects are investigated. In this work, the development of the proposed framework for systematic engineering decision-making is mainly motivated by the industrial requirements obtained from a set of online workshops and meetings with industrial experts from engineering and defense backgrounds. To validate the applicability of the proposed methodology and the correctness of the developed toolkit, a real case study derived from defence industry is also provided.

3. Technology Prioritisation Process Framework

In this section, the steps followed for the development of the proposed design framework for technology prioritisation in the TES context are discussed. The framework consists of four steps: (i) problems identification; (ii) technologies review; (iii) support activity assets prioritisation; and (iv) ROI analysis. An abstract view of these steps is illustrated in Fig. 1. The proposed framework develops a structured guide with customisable technical solutions that can effectively simplify the decision-making process by capturing, filtering and prioritising various technologies based on engineering and economic benefits.

Step 1 – Problems Identification: Reviewing the aim of the proposed design framework, a subset of technology solutions should be generated through a prioritisation process, which enables assets optimisation in terms of value and cost. This, thus, requires capturing the right range of technologies. It has been noticed that different stakeholders have diverse perspectives which directly influence the result. Therefore, the first step for the framework development is to identify the key problems in a given system and capture their requirements, employing the QFD method. The outcome of this step is based on two trade-offs balancing between the: (i) identified problems, ranked by customer's importance, and potential

approaches to solve them; and (ii) potential approaches and support activity assets, by evaluating factor relationships.

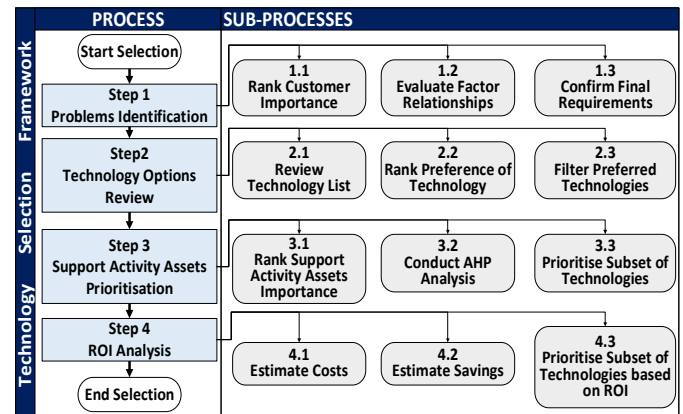


Fig. 1. Proposed Design Framework Process

Step 2 – Technologies Review: After problem identification, a set of technologies should be recommended in line with the recognised problem. This then leads to filter and narrow down the technologies by ranking their significance based on customer's preference. In order to capture technologies from various perspectives, three technology lists are proposed covering: (i) business requirements; (ii) engineering applications; and (iii) future trend. Hence, by ranking the technologies, this step filters the available options and reduce the potential solutions. Due to the complexity of technology requirements and problem context, the technology list generated in this study is not fixed, allowing further customisation. Using a priority level of 'High', 'Medium' and 'Low', decision makers can obtain the preferred list based on their views. For instance, 'High' is selected once technologies are viewed greatly suitable to solve the problem from step 1.

Step 3 – Support Activity Assets Prioritisation: Once decision-makers rank the list of technologies based on their preferences in step 2, a more detailed prioritisation process is conducted leading to a final technology selection. In this 2nd prioritisation, service resources known as support activity assets are considered as a set of attributes that can generate availability of assets. Within the TES context, the approach in [17] introduces five levers, namely *people*, *spares*, *information*, *test equipment* and *facilities*, for improving cost and availability. Inspired by the work in [17], step 3 prioritises technologies obtained from step 2 considering the aforementioned levers employing the "AHP" method. An AHP ranking scale, ranging from '1' to '9' (where '1' expresses identical importance and '9' much more importance), provides the assets criteria weight for technology comparison. Following this step, the process has converted the obtained technologies into a final subset of preferred technologies in terms of improving the support activity assets. Accordingly, this step promotes optimal values for major assets.

Step 4 – ROI Analysis: In parallel to the engineering analysis (output from step 3), the proposed framework can also prioritise the technologies obtained from step 3, in terms of the economic benefits that they can bring after their implementation. Research studies show that ROI analysis has been widely employed to various domains and brought

considerable benefits for technology decisions [18]. Thus, ROI analysis is conducted in step 4, providing a list in which the technologies obtained from step 3 are ranked based on their financial impacts. With a priority level of 'High', 'Medium' and 'Low', the costs and savings after implementing the selected technology are estimated. For example, for 'People – Level', if the training costs of operators to achieve a set of skills were a bit higher than the labour cost savings due to new technology, then the costs may be considered as 'High' and savings as 'Medium'. Then, the lists from steps 3 and 4 can be compared providing informative decision-making.

4. Toolkit Development and Demonstration

Following the proposed framework designed within the TES context, a dynamic Excel-based toolkit is also developed to visualise the application of this framework. The proposed toolkit converts the theoretical prototype to a practical model. This section discusses the step-by-step development of the Excel-based toolkit, demonstrating how to process the data flow and achieve desired functions. Based on the four steps introduced in section 3 for the design framework, the proposed toolkit is built.

Step 1 – Problems Identification: The QFD method is employed and three QFD matrices are developed to conduct a modular requirement analysis leading to the identification of the key problem. The three matrices are dynamically connected to each other. From the 1st QFD matrix, according to customer's requirements, the problem space (e.g. cost responsiveness, availability, etc.) and the best solution following the TES value streams (i.e. avoid, contain, recover and convert) are identified. An example of this 1st QFD matrix is seen in Fig. 2, where the customers want to minimise the *cost* by *avoiding* physical degradation. Similarly, the 2nd QFD focuses on finalising how to optimally solve the problem from the 1st QFD in terms of the TES value streams and what better allows us to fix the problem considering the TES support activity assets (e.g. people, spares, facilities, etc.). Each asset may be examined employing up to three variables, i.e. level, scale and location, where applicable. Fig. 3 illustrates this 2nd QFD for the example previously considered. It is seen that the best solution of the identified problem is to avoid asset's degradation by making changes to the level and scale of experienced people. Finally, in the 3rd QFD, the sub-processes correspond to the value stream from 2nd QFD with the highest ranking are automatically added and examined against the TES stages, i.e. data, insight, plan and act.

Based on experts' knowledge obtained from workshops, the TES sub-processes are the targets for technology application – the point at which we act to deliver tangible value [1]. For instance, the TES sub-processes for 'Avoid' can be design, manufacture and usage [2]. The TES stages also target for technology application converting data to actionable insight. Therefore, step 1 identifies the problems and relevant solution approaches. Fig. 4 demonstrates the output for the example considered. Finally, users are able to customise the outputs from step 1 based on their preferences and knowledge.

QFD1: Identify the KEY Strategic Target												
Column#		1	2	3	4	5	6					
Row#	Customer Importance	Process	Process in TES Framework				Row Weight Score CR priorities	What is the most important problems currently?				
		Customer Requirements ↓	Avoid	Contain	Recover	Convert						
		1	3	E.g. Availability	5	3			5	1	42	1
		2	2	E.g. Cost	3	1			1	1	12	2
		3	1	E.g. Risk	1	3			1	1	6	3
Process importance score		22	14	18	6	60						
Importance%		36.7%	23.3%	30.0%	10.0%	1						
Process priority rank		1	3	2	4							

What is the best way to solve the problems?

Fig. 2. Step 1 – Problems Identification: 1st QFD Matrix

QFD2: Identify the KEY Process and Capabilities																
Level: the different sets of skills Scale: the number or quantity Location: the physical location																
Customer		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 9	Level 10	Level 11	Level 12	Level 13	Level 14	Level 15
Direction of improvement (Worse/Better or Top/Bottom)		Worse	Better	Worse	Better	Worse	Better	Worse	Better	Worse	Better	Worse	Better	Worse	Better	Worse
Asset	Process	Asset in Through-life Engineering Services(Capabilities)														
		People	Spares		Test equipment		Facilities		Information							
1	3	Avoid	1	5	1	5	3	1	1	3	1	5	1	3	1	3
2	1/3	Contain	1	1	3	1	1	1	1	1	1	1	3	3	1	7
3	1/2	Recover	1	3	5	1	1	1	1	3	3	3	3	3	5	17.5
4	1/4	Convert	1	3	5	1	1	1	1	3	3	3	3	3	5	17.5
Asset importance score			2.063	7.083	4.75	6.083	4.083	2.063	2.063	4.083	2.083	3.083	3.083	3.083	5.75	4.083
Importance rank			0.03	0.12	0.08	0.10	0.07	0.03	0.03	0.07	0.03	0.05	0.12	0.05	0.08	0.05
A/R Priorities rank			12	1	3	3	6	12	12	5	12	10	10	4	9	8
Overall Rank			3		4		5		3		3		3		3	

What is the best way to solve the problems in terms of capabilities?

What allows us to fix the problems?

Fig. 3. Step 1 – Problems Identification: 2nd QFD Matrix

Output For Step 1							
Problem Identification	Framework Position			Rank	Recommended Capabilities	Final selection	
						Agree	Modify
Availability	Process	Activity	Stage	1	People		Spares
	Avoid	Manufacture	Act	2	Information	Confirm	People
				3	Facilities		Test equipment

Fig. 4. Step 1 – Problems Identification: Toolkit Output

Step 2 – Technologies Review: From step 1, the problem area and desired TES support activity assets that allow to solve the problem are identified. In step 2, the toolkit recommends a technology list where users are able to rank the importance of technologies based on their preference, experience and knowledge with a priority level including ‘High’, ‘Medium’ and ‘Low’. This helps to narrow down the technology options. Following the preference ranking, a sub-step for identifying new initiatives by adding technologies is also provided. Finally, the toolkit automatically generates a list of technologies including both the technologies denoted with ‘High’ importance and the options added by the user.

Step 3 – Support Activity Assets Prioritisation: An AHP analysis for each TES support activity asset from step 1 considering the list of technologies obtained from step 2 is carried out. Pairwise matrices for the technologies (from step 2) are automatically created and buttons automatically connected to these matrices are also developed in Excel. Additionally, the consistency rate of AHP matrix is automatically calculated to enable users check the logic of their ranking. After, comparing the importance of technologies for each asset, a final subset of prioritised technologies is obtained. Fig. 5 shows the technology prioritisation for each asset, including ‘spares’, ‘people’ and ‘test equipment’ after the AHP analyses have been carried out. By assuming equal weights for each asset, a chart prioritising the top five technologies based on support activity assets is developed in Fig. 6.

3.1 AHP For Technology Selection			
Spares	Spares	People	Test equipment
	Automation	Flexible fixturing	Agile Manufacturing
People	Total Quality Management	Robotic/cobotic assembly	Product Lifecycle Management
	Robotic/cobotic assembly	Automation	Automation
Test equipment	Flexible fixturing	Agile Manufacturing	Total Quality Management
	Agile Manufacturing	Total Quality Management	Robotic/cobotic assembly
	Product Lifecycle Management	Product Lifecycle Management	Flexible fixturing

Fig. 5. Step 3 – Support Activity Assets Prioritisation: Technology List

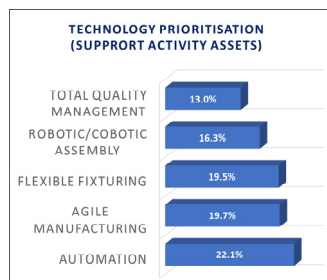


Fig. 6. Step 3 - Support Activity Assets Prioritisation: Toolkit Output

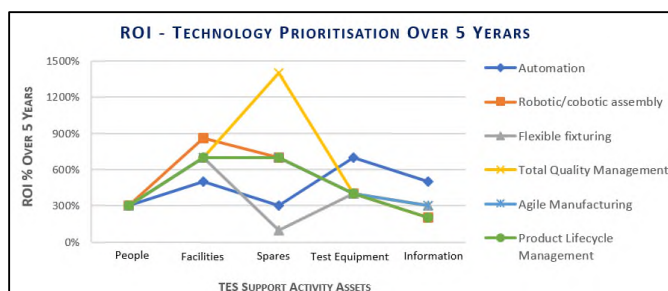


Fig. 7. Step 4 – ROI Analysis: Toolkit Output

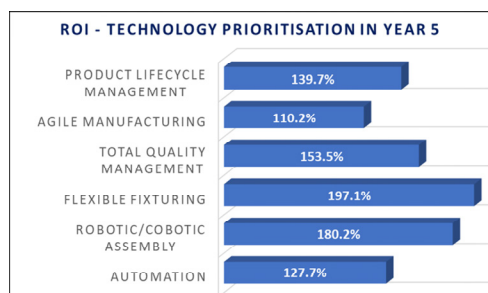


Fig. 8. Step 4 – ROI Analysis: Toolkit Output

Step 4 – ROI Analysis: Once the technology list should be assessed from a financial viewpoint, ROI in step 4 is conducted. Considering the application demands of people from different departments, engineers tend to evaluate technical opportunities from the perspective of assets, while financial or market personnel may focus on financial data. The toolkit has embedded calculating ROI for comprehensive decisions. After the users provide the costs and savings for each technology from step 3, the cumulative ROI for each technology over five years is calculated. Fig. 7 and 8 show two of the charts can be obtained from the ROI analysis. The graph in Fig. 7 shows the ROI over a 5 years' period for each TES support activity asset for the top six ranked technologies. Based on Fig. 7, the ROI analysis considering the costs and savings of 'people' shows that all the six technologies give a positive ROI of 300%. It is

also seen that the 'spares' for the 'Total Quality Management' technology give the highest ROI of all the assets in all the six technologies.

It is observed that the technology prioritisation can be viewed from two perspectives: support activity assets and ROI, which may provide different results. According to Fig. 6 technology prioritisation based on assets suggests that the best option to minimise costs is the automation, whereas based on the ROI over 5 years the product lifecycle management. This is an interesting feature of the toolkit as decision-makers can identify a range of possible outcomes and select the most suitable option based on their focus.

5. Design Framework and Toolkit Validation

By conducting a series of online meetings with two engineering experts (senior support consultant – 30 years' experience and support consultant – 20 years' experience) from the Ministry of Defence (MoD), the proposed design framework and dynamic toolkit are validated with the help of a real case study. The proposals in this study were applied within the defence context for equipment support availability, introducing a modelling system for the fidelity increment of supportability decision-making.

During the validation, following the process framework, the toolkit completed and feedback was collected from industry experts. A validation questionnaire considering the selected approaches and functions employed for the toolkit development has been also created. The feedback from industry shows that both the design framework and dynamic toolkit are well-structured and applicable, while can effectively prioritise technologies within the specified context and properly identify opportunities for technology improvements. It has been unanimously concluded that the proposed framework and toolkit enable identification of the root causes of losses and address the appropriate resources. Moreover, the prioritised technologies demonstrate to be reasonably generated from the user assumptions and the real data. Additionally, it was noted that the QFD method contributes to digging into the root cause and the real pain points. Finally, through the integration of engineering and financial views, systematic decisions can be made in terms of technology forecasting.

In order to visualise the maturity of the design framework and toolkit, three evaluation criteria namely completeness, applicability and reliability are set. Exploiting the information acquired from the questionnaires, average scores are calculated for the criteria and qualitative analysis is conducted. As viewed in Fig. 9, the highest scores, obtained in terms of users' feedback, indicate more agreement allowing us to discover where is the focus and make further improvements. In this scenario, the toolkit has demonstrated high completeness and reliability, satisfying the expectations of users, whereas, the applicability could be further optimised as the flexibility of customisation is high.

In addition to the qualitative analysis, feedback from the MoD experts is provided highlighting the validation results: (i) Following the 1st step of the toolkit, a real problem of 'reliability' is revealed to be more prominent rather than the initial highest customer priority on 'availability'. (ii) Following

the 3rd step, applying AHP analysis, a subset of technologies within defence context can be prioritised based on the comprehensive weight of support activity assets, and it indicates distinct priorities on different assets. (ii) A subset of technologies was prioritised after conducting ROI analysis, clarifying the potential financial effects.

Finally, two main comments made by the MoD experts, showing that the process works as planned, are: (i) “The toolkit is well-structured with clear approaches and applicable process steps”. (ii) “Both the process framework and the toolkit enable to prioritise technologies within the specified context and technology improvements can be properly identified”.



Fig. 9. Toolkit Validation

6. Conclusions

As the innovations of emerging technologies and their integration across industry become more vital than ever before, the decision-making process to prioritise various technologies within distinct contexts in a universal way is becoming more complex. Moreover, considering multiple factors align with strategies and policies, the current process of technology selection is subjective and challenging due to lack of reliable evidence of approaches and effective support for decision-making. Therefore, aiming to meet the aforementioned challenges, in this research work an innovative and comprehensive design process framework embedded in the TES context that ensures to efficient prioritisation of technologies was introduced. A dynamic Excel-based toolkit within the TES context which enables decision-makers to make informative technology selections in terms of business and engineering trade-offs was also developed. In accordance with the previous studies, this research work has integrated multiple methods for following a common TES framework that helps to establish specific processes, identify potential value streams and determine support activity assets, with the view to conduct a rational assessment and support the results. However, the expected benefit and impact of the proposed design framework and toolkit may ultimately depend on the efforts and commitments of the users.

The application of the innovative design framework and toolkit to real-case studies has demonstrated that they can effectively be used to prioritise technologies for various scenarios. The proposed approach can also support both

engineering and business perspectives and hence, boost more opportunities for technology improvements.

Future work would include further industrial application of the proposed approach and improvements according to feedback and customisation requirements with the view to enhance the applicability and flexibility of the process. Moreover, the dynamic proposal has left enough space to extend its data source and functionalities based on the problem area identified each time. This could serve as a basis for building a cross-industry technology database and facilitating collaboration. Last but not the least, a final step could be added to generate a single technology list, by combining these developed for the two perspectives, i.e. engineering and financial, employing a weighted sum method.

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