State of the Art in Through-life Engineering Services

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State of the Art in Through Life Engineering Services

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State of the Art in Through-life Engineering Services

Abstract

Through-life Engineering Services (TES) involve the use of applied technologies in support of complex engineering products. TES is considered to be a key enabler of innovative product support strategies and business models achieved by condition-based monitoring, applied prognostic and diagnostic technologies, aligned Maintenance Repair and Overhaul (MRO) strategies, and integrated service delivery systems. This paper presents the findings of a state-of-the-art review of the literature relating to TES. Contributions to the literature are identified by application of a structured and defined method, which are then collated and analysed. The findings are grouped into a number of themes which include definition, structure, scope and standards that govern TES. Further findings report examples of TES applications, features in the effective design of TES solutions, tools and methodologies for designing TES in support of complex engineering products, and offers discussion of the ongoing and future direction for TES.

Keywords: Through-life Engineering Services, Condition Based Management, Maintenance Repair and Overhaul, Service Delivery Systems

1 INTRODUCTION

Through-life Engineering Services (TES) are the result of the evolutionary progression in the development of applied technologies which enable the enhanced support of complex engineering products [1] [2] [3]. Whilst the emergence of TES is facilitated by developments in technology and innovative applications thereof, two of the underlying drivers for increased levels of product support are Product Service Systems (PSS) [4] [5] [6] [7] and the process of *servitization* [8] [9] [10] [11]. Underlying the adoption of PSS through increasing levels of *servitization* there lies the issue of increased levels of risk transferred to the product's manufacturers. This manifests itself as the manufacturer adopts risk to the revenue stream caused by the diminishing or loss of a product's design function when offering contracts based upon the availability for use of their products.

Product Service Systems emerged as a result of consideration for the sustainability of resource (predominantly ecological risk) as demand for products continued to increase [12] [4] [13], whilst *servitization* is seen as a strategic response to business risk [8] [14] [15] [16] resulting from such commercial pressures as globalisation, low cost economies, and the need for protective operating strategies to maintain and improve on the organisation's competitive position [17]. These two strategies provide increased levels of 'data' which can be used to facilitate continuous product and service improvements, and improved revenue streams in economic downturns. The technical data generated when operating PSS and servitized solutions can also be leveraged to reduce risk by informing advanced engineering service and support strategies one of which is Through-life Engineering Services.

As manufacturing organisations move through Tukker's [18] [19] PSS continuum there emerges a fundamental shift in the flow of revenue between the manufacturer and the user of the product, and in the case of high value complex engineering products, the finance house. Baines et al illustrate this in their work relating to PSS and *servitization* [7] [20]. Baines proposes three levels of service that manufacturing organisations move through as they evolve through the servitization process and the authors have sought to illustrate this by adopting and amending Baines's model (**Figure 1**).

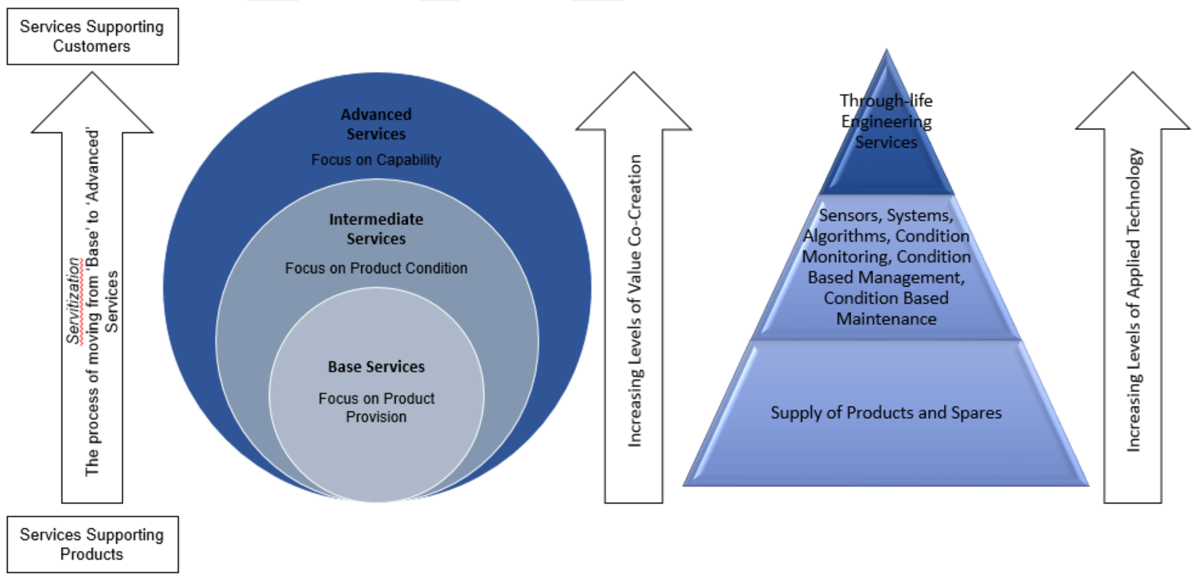

Figure 1: Applied Enabling Technologies for Differing Levels of Service

[Modified from Baines [21]

In Figure 1, we see that Baines [21] identified three levels of service which move from being centred on product provision, through managing the product's condition, to that of supplying a capability based upon the product's design function. Two typical examples of advanced services being:

- Rolls Royce moving from selling engines to selling the availability to deliver 'thrust' on demand.
- Xerox moving from selling office copying machines to selling managed print solutions

As advanced services evolve the concept of wealth being increasingly co-created emerges [22] [23] as organisations seek to become ever closer aligned to the product service offerings of their customers. In so doing the ability of their products to reliably deliver the design function becomes ever more important to their revenue streams. The authors suggest that as organisations enter into availability contracts this risk to the manufacturers revenue due to degradation or failure of the product's design function warrants significant focus. Manufacturing organisations will seek to mitigate potential disruption to their revenue streams and subsequent damage to brand reputation should product performance degrade or fail when in use. It is suggested by the authors that this adopted risk to revenue by the manufacturer over the operational/contract life of the product gives the impetus to the integration and embedding of applied technology within their product support offering. Such technology gives advance warning of system and component degradation. As the service offering becomes increasingly advanced and revenue value co-created this risk becomes ever greater and is mitigated by increasing levels of applied technology as illustrated in (**Figure 1**).

Product support strategies offered by manufacturers facilitated by the application of sensor and computational technologies serve to mitigate product degradation by providing component and system monitoring, triggers for action, 'in use' diagnostics and remaining useful life prediction. The application of sensors seek to monitor performance and mitigate the risk whilst the product is '*in use'* (or after use through condition data downloads) thus informing the '*use/do not use*' decision. These solutions also aid informed Maintenance, Repair, and Overhaul (MRO) functions. Collectively, these examples of applied technology as applied to support of the product has the potential to extended the product's availability for use aided by the application of this acquired service knowledge within the design function [24].

This paper presents a review of the literature relative to Through-life Engineering Services (TES). It is seen as an applied engineering product support strategy which facilitates the reduction of various operational and business risks to the manufacturer when competing through PSS and servitized operational strategies. The research aim, scope and research questions are presented in (**Section 2.1**). Key research themes are identified through analysis of the literature and the findings presented (**Section 3**). The structure of the literature relating to TES is also presented illustrating 'hot spots' within the current research (**Section 3.2)**. A discussion and suggestions for future research are given in (**Section 4**) followed by concluding comments which are presented in (**Section 5**).

2 RESEARCH PROGRAMME

2.1 Aim, Scope, and Research Questions

The aim of this paper is to identify contributions to the literature relating to Through-life Engineering Services (TES), by collating the literature identified and presenting an analysis of the contributions so as to answer the five research questions which follow. The scope of this paper seeks to include all contributions which are identified as being relevant when applying the selection strategy in section 2.2, to developing a detailed understanding of the TES concept, its content, application and context. The focus of the study is upon the 'through-life' elements of service support offerings as applied to complex engineering products whilst specifically *excluding* the asset management literature as this typically aligns to infrastructure assets (e.g. civil engineering structures, rail and road networks, telecommunication networks, energy grid and associated infrastructure etc). In addition, the literature directly relating to '*maintenance*' unless explicitly associated with TES within each contribution has also been omitted from the search strategy as to have included this would have resulted in a volume of contributions which would have been far to excessive for the publication constraints of this paper.

For the purpose of this research, the authors adopt the definition of a 'high value *complex engineering product'* as:

> *"… a product which can be electrical, mechanical, electro-mechanical, or a combination of all three, which is an assembly or sub-assembly capable (or potentially being capable) of the supply of utility to the user or operator by way of its operating and service system integration through-out the product's life-cycle"* [25].

Typically, such products include aircraft, automobiles, trains (rolling stock and locomotives), military equipment, marine products, mineral extraction plant and equipment (oil rigs, tunnel equipment, high value mining products etc), energy generation products (turbines), medical machines (scanners, dialysis machines etc), machine tools and sub-assemblies thereof.

This paper proposes the following research questions which were defined following a series of workshops and discussions attended by groups of invited academics and industrialists who represented organisations identified as having an interest in, or seeking to adopt TES. They were also informed by a review of survey data which has been previously reported by Grubic et al [26].

The research questions developed from the above workshops and discussions are:

***RQ1**: What are Through-life Engineering Services and how are they defined?*

***RQ2**: What is the scope of Through-life Engineering Services and how do they*

relate to other product support services?

***RQ3**: Where are there leading examples of Through-life Engineering Services?*

RQ4**: What are the enablers and inhibitors to the technical and commercial success of Through-life Engineering Service**s

***RQ5**: What are the opportunities and challenges to address in the future development and adoption of TES?*

These questions served to guide us in our search for the relevant literature.

2.2 Search Strategy

The strategy adopted for this literature search is formed by the identification of suitable sources from which the data can be obtained. The data sources used included peer reviewed journals, conference papers, authored and edited books, magazine and media articles, recorded digital media (blogs, web posts etc). In selecting data sources standard library e-resources were consulted using "*Engineering*, *Manufacturing and Creative Design*" as top level filters. The second level filters were related to "*Reliability and Maintenance*" which offers 'Scopus', 'ABI Inform', 'AIAA', Association of Computing Machining', 'Business Sources Complete, 'IEEE Xplore' and 'Web of Knowledge, databases as relevant sources for the literature search. The time frame used was initially defined as being from 2000 to 2016 with the citations within the literature returned being reviewed to ascertain if there were any earlier relevant publications.

The literature search was informed by the use of several key words and search strings that had perceived relevance to TES and had been identified as being aligned to the focus of this research during discussions with fellow researchers working in this arena. TES are seen as a broad concept relating to the engineering product support offered by service delivery systems. It was therefore necessary to employ varied numbers of search strings across all of the selected databases in order to identify and capture the aligned contributions to the literature. Typical Key words and search strings used are listed in tables **1a** and **1b** respectively.

Table 1a: Key Words Used in Literature Search

Total Health Management	Maintenance Repair & Overhaul	Condition Based Maintenance
Whole-Life Engineering	Autonomous Maintenance	Intelligent Maintenance
Life-Cycle Engineering	Condition Based Management	Integrated Vehicle Health Management
Product life-cycle Management	Intelligent Maintenance	Self-Healing
Through-life Engineering Services	Through-life Degradation	Component and System Degradation
MRO Data Trending	MRO Software Platforms	Systems Integration
Systems Led Logistics	Service and MRO Standards	TES Codes of Practice
Service Led Design	Maintenance Systems	Warranty Systems
Quality Systems and TES		

Table 1b: Typical Key search strings and Boolean Operators used in the literature search

- TS=(Through life Engineering Services)
- TS=(Through life Engineering Services **NOT** Health)
- TS=(Through life Engineering Services **AND** Total Health Management **NOT** Health)
- TS=(Through life Engineering Services **AND** Maintenance Repair and Overhaul)
- TS=(Through life Engineering Services **AND** Self Healing)
- TS=(Through life Engineering Services **AND** Self Healing **NOT** Health)……etc

The search strategy served to identify literature sources that *directly* linked TES to the Key Words. In searching for TES alone there were over 1900 papers returned. However a review of titles identified that the vast majority of citations were not focussed upon the engineering and support of complex engineering products, but rather research relating to the medical and Natural Science fields. To filter out these contributions the 'NOT' Boolean operator was employed. This proved partially successful but the output still required a manual filter of the titles returned at each stage of the search strategy which resulted in the number of papers returned at each stage as illustrated in **Figure 2**.

Finally, a search of the Internet was undertaken for general (non-peer reviewed) documentation (blogs, social media, magazine articles etc) a review of which, together with the aforementioned searches returned the following results.

2.3 Results and Analysis

This paper presents the findings of a structured literature review the methodology and search strategy for which, whilst not following their framework explicitly, is inspired by Tranfield et al [27]. The search strategy returned a large number of cited contributions which relate to the search strings and keywords applied (**Table 1**). The results of the literature search and subsequent filtering yielded 135 papers which had direct relevance to the focus of this study (**Figure 2**). It is the analysis of the content and structure of this literature which provides the basis for this literature review. The sections within this paper are the result of mind mapping techniques and cluster analysis the results of which form the reporting structure for this paper.

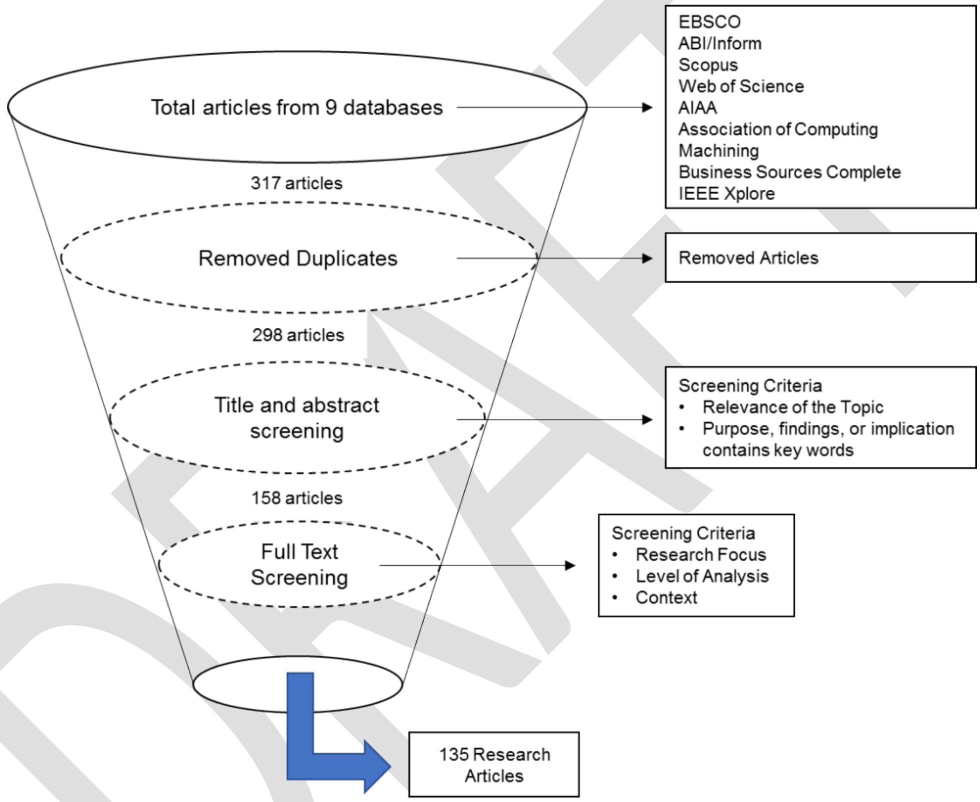

Figure 2: Literature Selection, Filtering and Review Structure

3 GENERATION OF KEY FINDINGS

In seeking to answer the five research questions this literature review has identified seven key findings which are presented and discussed in the following subsections of this paper.

3.1 Definition of Through-life Engineering Services

Discussion relative to the identity, content and context of Through-life Engineering Services continues to increase since first appearing in 2009/10. This review of the literature sees no clear definition for TES emerging which relates to, and includes the *content, purpose, and context* [28] of the concept until 2014. In their research Baines et al [7] state that "*clear definitions are an essential starting point for all research*" and guided by this principle, we adopt this as the starting point for this review. Prior to 2014 there are few definitions which seek to fully define TES using the dimensions cited above (i.e. identity, content, and context) with many of the published descriptors opting to focus upon the supporting and enabling technologies and the result of their application thereof. Whilst few definitions existed prior to this point we have listed several definitions which were identified in their search of the literature and which have an explicit or implicit association with TES and include elements of dimensions defined (**Table 2**).

In reviewing these tabulated definitions it is observed that many focus more on the purpose of, and results from, the application of TES rather than offering definitions which relate to the dimensions stated above. We suggest that it is interesting to note that upon review of the papers published in the Proceedings of the 1st and 2nd International Conference on Through-life Engineering Services (132 papers) that *none* seek to offer a definition for TES [3].

Redding [3] discusses the merits of the definitions identified pre-2014 by Aurich et al [29], Hauschild et al [30], Meier et al [31] and Roy [24]. In Redding's analysis and discussion of the aforementioned contributions and those listed in (**Table 2)** he cites Davenport et al [32] when suggesting that "*implicit in the discussion*…[re: definitions] *thus far is the role of service data information from which knowledge and …wisdom can be applied relative to the product*" [3]. This is also noted by Jagtap and Johnson [33] when stating that the "….flow of information from the service domain to designers is….crucial for minimising in-service issues and can also reduce the cost of both planned and unplanned maintenance" [33].

The literature offers many contributions relative to the links between data, information and knowledge. In previous publications, we suggest that to have value these three levels of this continuum require the same "*the content, context, and structure for* each *of these dimensions ranging from definitions of each dimension* [34] [35]*, its structure and management* [36] [37] [38]*, the comparison between semantic and syntactic knowledge structures relative to storage and retrieval systems* [39]*, and studies as to how service knowledge can be used to benefit design* [40] [41] [42]*".*

Finally, a consultation paper [43] presented by the EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services at a launch event held at the UK Houses of Parliament (10th September 2015), gave the following definition:

> *"Through-life Engineering Services – TES – encompass the design, creation and in-service sustainment of complex engineering products with a focus on their entire life-cycle, using high-quality information to maximise their availability, predictability and reliability at the lowest through-life cost"* [43] [44] [45]

This is definition again stresses the whole life nature of TES whilst acknowledging the requirement to harvest, analyse, and utilise data in order to promote the products maximum availability for use whilst seeking to achieve the lowest life-cycle cost.

Table 2: Dimensions of Definitions relating to Through-life Engineering Services found within the literature

Author	Identity	Definition	Content	Context
Aurich et al [46] [47]	Technical Product Service Systems (t-PSS)	*"With respect to the understanding of technical Product-Service Systems and their non-physical components… three constitutive characteristics can be identified, which distinguish technical services from physical products:* • *Technical services are mainly non-physical. Their realization can therefore often be performed at minimum consumption of resources, which is one of the decisive reasons for services being considered in the context of dematerialization. Furthermore, due to their non-physical character, services can neither be produced to stock nor distributed like physical products. Hence, the service provider must build up corresponding resources for 'on demand servicing'.* • *Unlike physical products that are first manufactured and later consumed over a period of time, technical services are realized and consumed simultaneously. This principle is referred to as the 'uno acto principle'* *The realization of technical services requires the integration of the customers in terms of providing the products, respectively, staff, to which a service (e.g. maintenance and user training) refers"*	• Resources for 'on demand' services • Integration with customers	• Non-physical services • Minimum use resources • De-materialisation • Resource realised and consumed simultaneously – '*uno acto'* principle
Hauschild et al [30]	Life Cycle Engineering (LCE)	*"..the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, whilst encouraging economic progress, keeping in mind the need for sustainability, at the same time optimizing the product life-cycle and minimizing pollution and waste…".*	• Application of technological and scientific principles to design of products	• Conservation of resources • Environmental Protection • Sustainability

Meirer et al [48] [49] [31]	Industrial Product Service Systems (IPS^2)	*"…is characterised by the integrated and mutually determined planning, development, provision, and use of product and service shares……… in Business to Business applications and represents knowledge-intensive socio-technical system. This means in detail…..* • *An IPS^2 is an integrated product and service offering that delivers value in industrial applications* • *IPS^2 is a new product understanding consisting of integrated product and service shares.* • *IPS^2 comprises the integrated and mutually determined planning, development, provision and use.* • *IPS^2 includes the dynamic adoption of changing customer demands and provider abilities.* • *The partial substitution of product and service shares over the lifecycle is possible.* • *This integrated understanding leads to new, customer-adjusted solutions.* • *IPS^2 enable innovative function-, availability- or result-oriented business models"*	• Integrated Product Service offering • Integrated and mutually determined planning, development, provision and use • Results orientated business model	• Product and service shares • Knowledge Intensive Social-technical relationship • Product/service sharing • Knowledge Intensive Social-technical relationship • New customer adjusted solutions
Redding et al [50]	Through-life Engineering Services (TES)	"*Through-life Engineering Services are the application of explicit and tacit 'service knowledge' supported by monitoring, diagnostic and prognostic technologies and decision support systems whilst the product is in use, and the application of maintenance, repair, and overhaul functions to mitigate degradation, restore 'as designed' functionality, thereby maximising product availability, thus reducing whole life cost*"	• Application of explicit and tacit 'service knowledge' • Monitoring, diagnostic, prognostic technology	• Reliability • Degradation Mitigation • Maximising product availability • Whole life cycle cost reduction

			• Decision support technologies • MRO Technologies	
Roy et al [24]	Through-life Engineering Services (TES)	"*Technical services that are necessary to guarantee the required and predictable performance of an engineering system throughout its expected operational life with optimum whole life cost*".	• *No content offered in definition* • *Purpose cited (listed in context)*	• Optimum whole life cycle cost • Reliability
Shaw et al [51]	Through-life Engineering Services (TES)	*"…..*[are]*….a novel dimension in engineering services which seek to cover the totality of technical services rendered during the lifecycle of complex engineering…..*[products]*…."*	• *No content offered in definition* • *Purpose cited (listed in context)*	• Complex engineering systems • Life-cycle
Tasker et al [52] [53]	Through-life Engineering Services (TES)	*"…(TES) is the collaborative provision of a holistic customer capability (the ways and means of capturing value will vary over time) based on the assured readiness and availability of complex engineering …products. The system boundary is set to ensure the service delivery is most effective and risk is appropriately distributed across the …[service] delivery network".*	• *No content offered in definition* • *Purpose cited (listed in context)*	• Collaborative provision of holistic customer capability • Complex engineering products • Assured readiness and availability

Finding 1

A definition for Through-life Engineering Services has continued to evolve with no single definition appearing which seeks to satisfy the requirement of having an identity, content and context. In seeking to satisfy this requirement and having mapped the contributions identified, we offer the following definition for TES:

> *"Through-life Engineering Services are the application of existing and emerging product and/or system monitoring, diagnostics, and prognostics technologies, supported by state of the art maintenance, repair and overhaul practices, methodologies, and strategies, which seek to mitigate risk to the ability to deliver a product's (or system's) design function through component (or system) degradation or failure, whilst offering a sustainable solution at minimum whole life-cycle cost.*

3.2 Structure of the Through-life Engineering Services Literature

In reviewing the contributions to the literature returned by the search strategy that we applied (**Section 2.2**), each publication was recorded and tabulated by author, date, institution, location, title, publication media, content and keywords. The data were then coded in Excel format and analysed to identify trends emerging. The findings generated in (**Figure 3**) illustrate that whilst the engineering and systems technologies are well covered, there is also interest in the roles of Artificial Intelligence, Autonomy, Augmented Reality and Cyber issues. It is also observed that there is a lesser focus on how these developments could be introduced and implemented through an increased understanding of business and cost models, standards and codes or practice, and the formation of strategies to implement change seeking to aid the adoption TES solutions within the manufacturing base.

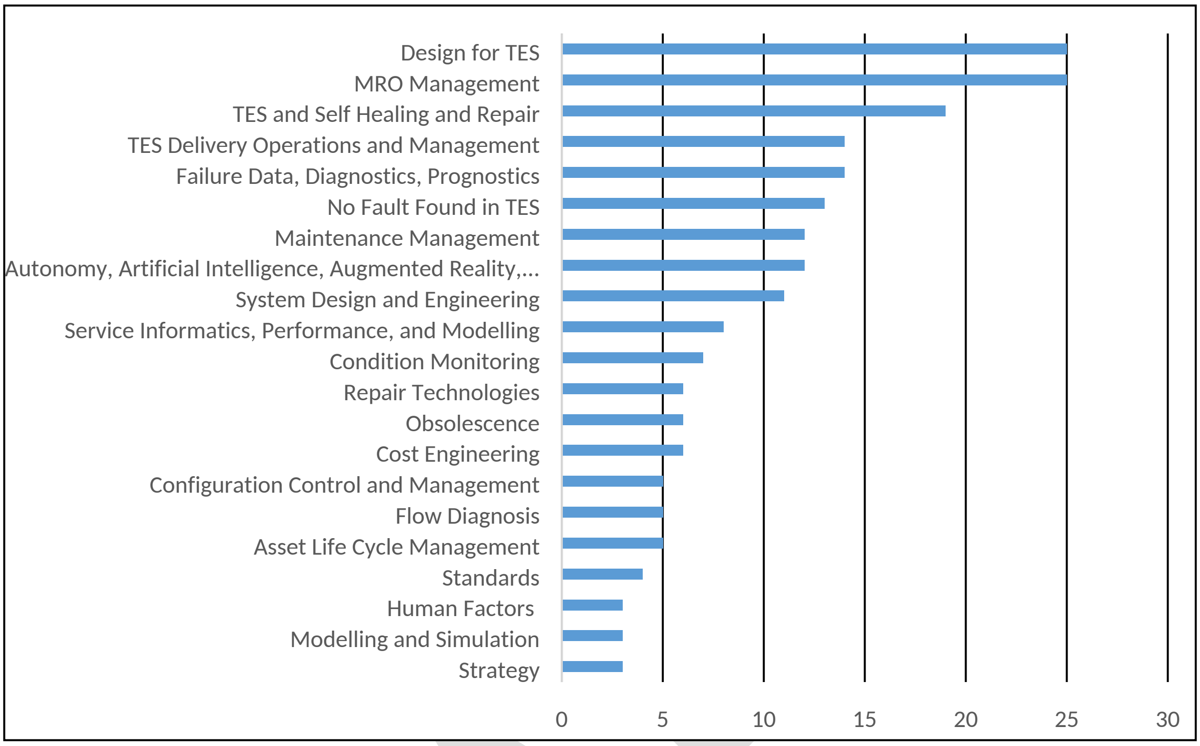

Figure 3: Grouped TES themes identified within the literature as percentage of the literature returned

Upon further review of the structure of the metadata returned it can be observed that several well defined hotspots (institutions and authors) exist from which the literature emerges. The majority of contributions directly relating to TES and its applications originate from Cranfield University (UK), with Lulea University (Sweden), Durham University (UK), University of Bremen (Germany), University of Twente (Netherlands) and IPK Fraunhofer (Germany) also making significant levels of contribution. When assessing the contributions of the lead authors it is found that the *average* number of contributions from the 135 papers reviewed is 2 papers with the top four contributing first authors being Uhlmann [54] [55] [56], Lindstrom [57] [58] [59], Farnsworth [60] [61] [62], and McWilliam [62] [63] [64]. When reviewing the second authors it was observed that Shehab [65] [66] [67], and Roy [24] [68] [20] [69] all figure strongly. In terms of the geographic origin of the contributions it was observed that the majority of the literature emerges from Western Europe (UK, Sweden, Germany, Spain, Italy), the USA, and Japan. It is interesting to note that very little emerges from Asia and none from the Southern Hemisphere economies.

Finding 2

The literature relating to Through-life Engineering Services emerged in Western Europe, the USA and Japan. It focuses on the support of complex manufactured engineering products through the application of applied technology. The majority of the contributions are seen to have been from academics and researchers who have 'predominantly' published in the Annual International Conference in Through-life Engineering Services and two edited books.

3.3 Standards in Through-life Engineering Services

When defining what is meant by standards we use the informal descriptions used by the British Standards Institute when stating that there are:

- Technical Standards – "…which deal with technical and material attributes such as material properties and standards for calculation"
- Process Standards – "…which articulate best or recommended practice for business processes"
- Framework Standards – "…which support best practice, enterprise level operational performance, and organizational behaviour" [53]

Whilst the literature has many contributions relating to standards and codes of practice in all disciplines, it offers very little relating to TES for any of the above with no direct standard(s) emerging. Contributions which seek to address this lack of guidance (i.e. Standards) are observed to be emerging from a small group of academics and researchers [51] [52] [53] working at Cranfield University in collaboration with the BSI (UK) and key industrial partners to their research. We suggest however that a lack of formal guidance relating to the development of a standard can be attributed to the lack of a formally adopted definition and identity for the TES (**Finding 1**).

In the first paper that deals directly with this subject Shaw et al [51] develop a 'draft' vocabulary which focuses '*their*' key areas which include "maintenance, repair and overhaul (MRO)" and "Obsolescence Management (OM)" in order "*to promote a common understanding of the TES vocabulary*" [51]. In so doing they propose key areas of TES that require standardisation either through the drafting of new standards or modification of existing standards to align with TES. They also observe that there is a need to identify and standardise the terminology, ontology and taxonomy for TES. Shaw et al suggest that "*…the human aspect is one of the main considerations of service within TES*" [51] but contributions relating to the human influences and factors associated directly with TES do not start to appear until the 2nd International Conference when Ramanen et al [70], Mannonen and Holtta [71], and Luoto [72] present their work looking at the links between knowledge management and the team.

Shaw et al [51] also identify 83 existing associated standards that they suggest are *relevan*t to TES and through their analysis identify 203 terms (140 existing and 63 new) which relate to the concept. In summarising their study in 2012 they state:

> "*The development of standards is ……the mark of a maturing industry but in TES there is an opportunity to…..define these standards early and hence gain advantage for UK industry*" [51]

Since their initial work Shaw and Tasker (Cranfield) and, Kelly and Sheridan (BSI) have continued to develop the foundations for a set of unifying standards relating to TES [52] [53] [73]. In their paper Tasker et al [53], whilst seeking to understand and define further the "…innovation and the role of Standards" [53], observe that there continues to be a "…lack of understanding or consensus.." relating to the identity, content and scope of TES, and therefore a lack of understanding as to the need for a new standard, or indeed expanded coverage of existing standards. This again aligns to ***Finding 1*** of this paper.

The requirement for a standard is seen as being critical to the commercialisation of emerging innovations and concepts [74]. This is asserted by Tasker et al when suggesting that "…*innovations*…[have]… *different*...[levels of]…*maturities*…[and].. *..benefit from varying approaches to standardisation*" [53]. In building their argument they state that as TES matures any such initial standard needs to define "..*vocabularies and semantic standards*" which facilitate effective communication of specialised information. There is therefore a need for standards that define architectures and testing as the offering becomes commercialised. This promotes 'confidence' and 'quality'. In the specific case of TES generic applications the challenge is to apply a combination of existing technologies (and their associated standards) together with emerging applications and innovations which seek to act as change drivers (disruptive and incremental) and newly authored guidance [53]. Whilst not within the defined scope of this paper, an example of this is illustrated by the evolution of the PAS-55 standard into ISO-55000 in the field of Asset Management.

Pliska et al [51] suggest that this exemplar transition is driven from the 'bottom up' and is typical of the practice of standards derivation to date. They suggest the application of Ng et al's [75] 'Common Integrating Framework' to identify the areas of TES that standards might need to address. They apply this framework whilst assessing the transition from PAS-55 to ISO-5500 with Pliska et al offering a model which it is suggested can be used to develop the focus and scope for an emerging standard for TES. Whilst their work acts as a waymark towards the development of a future standard no substantive or definitive progress in addressing the actual content of the standard is achieved.

Finding 3

Since the need for a standard (and codes of practice) for TES was identified in 2012 there have been several ongoing joint initiatives with academics, practitioners and a UK Standards Body (BSI) seeking to define a 'road map' to a National Strategy for TES and an aligned Standard(s). However there is no Standard or codes of practice emerging which offer Technical, Process or Framework guidance directly aligned to TES.

3.4 Scope of Through-life Engineering Services

This review of the literature would suggest that the scope of Through-life Engineering Services lacks boundary and continues to grow with few attempts to define the 'bandwidth' of this rapidly emerging application of technology in support of the complex product from a 'whole-life' perspective. We have suggested that this could relate in part to there not being a widely accepted definition for TES (**Section 3.1**). There has been little attempt to define a taxonomy for TES and again nothing that has been widely adopted. Following on from the Redding's [76] first attempt to trigger discussion relative to the scope, whereby an elementary structure for TES was offered, we have, again, reviewed the literature identified as relating to TES (**Section 2.3**). Through the application of mapping techniques and discussion with fellow academics and practitioners in the field the following sub-sections present a possible bandwidth (and therefore scope) for TES.

3.4.1 TES Generic Product Support

The use of TES generic solutions in support of complex engineering products appear in many forms. These are identified in the literature and manifest themselves as a complex strategic mix of applied technologies. These technologies range from basic to advanced workshop based maintenance, repair and overhaul (MRO) technologies, supported by various levels of MRO facility based product diagnostic and prognostic technologies. These can deliver real (or near) time design function degradation data and supporting failure mitigation strategies which include Condition Based Monitoring and Condition Based Management applications enabled by applied sensors, computational algorithms, and communication applications. The increasing levels of added sensors and advanced computational applications, which can be either on or off product, and the connectivity of the product to remote monitoring/management platforms is resulting in evermore complex product support solutions which in turn have the ability to define the business model. Examples of such solutions are discussed in (**Section 3.5**) of this paper.

3.4.2 Communication and Data Transmission Technologies (CDTT)

The application of sensor technologies to the product in order to monitor and manage product performance is seen as being an effective strategy to increase the product's availability for use. There are many examples documented in the literature which adopt this strategy [77]. Typical sectors applying these technologies include aerospace [78] [79] [80], military vehicles [81] [81], automotive [82] [83], rail locomotion and rolling stock [84] [85] [86] health [87], machine tools [88] and Smart Metering applications [89]. The communication of harvested sensor data (and information) is an essential element of TES product support solutions. The means of transmission of data from the product to the receiver can take the form of either (or a combination of) land based, radio, or satellite technologies in the case of real (or near) time applications. Data transmission can also be initiated after a period of delayed 'on board' storage and this often takes the form of RFID transmission when passing a collection node. A typical operation and structure for such a solution is illustrated below (**Figure 4**).

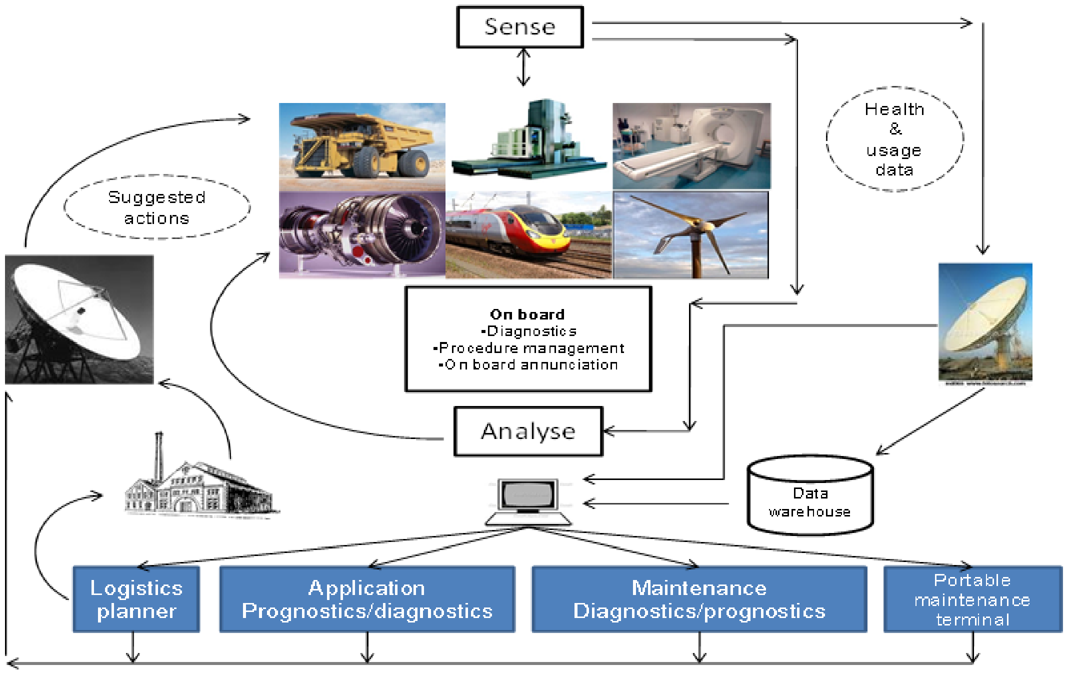

Figure 4: Operation and structure of an TES generic communication and data transmission network (Adapted from [77])

Whilst not within the scope of this research paper, we observe that the increasing developments in digital technology (e.g. sensors, computer technology, algorithmic design, and communication connectivity) is growing at a near exponential rate. Through this lens a new body of literature is growing that seeks to understand and develop these technologies focussing upon the 'connected product' and 'cyber physical systems' [90] [91]. These systems and the increasing levels of data that are generated from them are themselves generating challenges and opportunities related to the scale of data available (e.g. Big Data) [91] [92]. The increasing development of these interconnected technologies sees the emergence of the Internet of Things (IoT) [93] [94] [95] as a technical phenomenon which can be leveraged in support of Though-life Engineering Services. These concepts and the challenges and opportunities that they present in relation to TES are part of the Fourth Industrial Revolution [96] [97].

3.4.3 Business Models and Tools

The literature appears to be sparse when seeking to identify contributions that seek to identify and assess the *explicit* business models that are currently applied in organisations that actively compete using TES enabled product support systems. The majority of the literature existing addresses the technology aspects of these applications and tend to focus upon Integrated Vehicle Health Management (IVHM) and Condition Based Monitoring (and Management) (CBM) solutions with very few relating explicitly to TES.. Whilst there are several cited examples of manufacturing organisations who are competing through advanced services (**Section 3.5**), such contributions offer an overview only of the results of such application when competing through servitized strategies enabled in part by TES.

We digress slightly at this point and whilst not focusing on TES directly. lessons are to be learned when reviewing the contributions of well-known senior academics working in the areas of servitization and strategy. Neely et al [11] [98] [99] have researched and reported on the growing trends relating to servitization and discussed the financial consequences resulting from its application in manufacturing whilst Benedettini et al [100] offers insight as to why organisations who adopt a servitization strategy within their competitive offering fail. It has been illustrated in this paper that such organisations seek to maximise the product's availability for use by reducing or mitigating failure to deliver the design function through TES generic solutions.

Baines et al [101] [102] [103] [104] offer contributions in the areas of strategy formation and formulation for manufacturers seeking to offer advanced services in support of their products and within their supply chains. Whilst such contributions offer valuable guidance for the organisation's positioning of its product offering and competitive space [105] [104] [20] there are very few contributions that signpost the road map for this transition by way of validated and verified strategies.

When organisations seek to adopt TES solutions the need for effective cost modelling to ascertain and mitigate risk becomes evident. This is clearly identified within the literature by Pour et al [106], Baguley [107], Kirkwood et al [66], Raza and Ulansky [108], and Erkoyuncu and Roy [65]. These authors all offer alternative modelling techniques that can assist in developing the understanding of risk associated with, and due to, cost when adopting TES strategic initiatives. Erkoyuncu and Roy [109] and Sandborn et al [110] are also offering greater insight into planned obsolescence and the associated cost risks at end of the product life-cycle. Sandborn focuses upon 'Diminishing Manufacturing Sources and Material Shortages (DMSMS)' resulting from the unavailability of technology or spares to maintain the product or system. It is seen that such risk is significant within a TES system and that the ability to forecast such events is advantageous when wishing to plan and mitigate adverse cost events. Sandborn offers consideration and contribution in the areas of Reactive Obsolescence Mitigation, Strategic Obsolescence Management, Software and Human Skills Obsolescence, all of which can have significant impact when designing a cost model for TES.

3.4.4 Strategy, Standards and Governance within TES

The role of standards and codes of practice are essential to sound and robust governance within TES. This is clearly identified during discussions with industrial practitioners and academics [73] working within the field seeking to develop a guidance document by way of a National Strategy for TES [44]. The need for the development of a strategy was initiated at the UK Parliament in September 2015 and the setting up of a steering committee to oversee its development followed with Rolls Royce Plc and the UK High Value Catapult launching a National Strategy for TES on the 5th of July 2016 at the Institution for Engineering and Technology (IET) in London. However whilst the need for such a strategy is well documented within the supporting publications [51] [53] [73] [52] the identity by way of a robust definition and scope for TES is not offered. The requirement for a set of standards based upon these dimensions has been previously discussed in previous sections of this paper (**Section 3.3**).

3.4.5 Inventory and Logistics Support

Traditionally logistic solutions have been in response to a defined requirement which is either lagging in nature or in response to an estimate of the frequency of future spares consumption. The literature contains a wealth of contribution which discusses the merits of Material Resource Planning (MRP) systems and lean and agile manufacturing systems in support of the product. Whilst the definition for TES offered in (section 3.1) of this paper makes no direct reference to the impact of its application on the fields of inventory and logistics contributions within the literature identify the potential for autonomous logistics as a pro-active enabler of logistic and inventory supply [111]. Martinetti et al [112] focus upon the initial spare parts assortment for capital assets by offering a structured approach which aids the initial spare parts assortment decision making (SAISAD). In their contribution they illustrate the Sprinter Light Train of the Netherlands as a case study in which they highlight the risks to capital when making ordering decisions for spare parts. If parts are under-ordered then loss of design function is a significant risk. If parts are over-ordered then this can lead to a significant increase in costs (cost of manufacture, holding costs, and on-self degradation costs). Their solution offers a decision framework based upon each component's criticality and Long Term Availability. This however only addresses the pre-production problem and the MRO support thereof.

Sabaei et al [113] propose '*Defence Support Services'* (DS2) for the UK Royal Navy as being a Product Service System [a TES] offering product support services by way of availability and spare parts contracting. In consideration of the latter, "lead time and overall cost are the two main dependant variables across the supply chain" [113]. They identify the reduction of these variables as being a key challenge to the competitive success of the players within the supply chain. In their research they propose a framework for a trade-off analysis between cost and time when seeking to inform the spares and logistics support decision. They also identify location of inventory as being significant and whilst not being directly relevant to the logistics problem, introduce the application of Additive Manufacturing as a solution to geographic problems.

It has been identified that a feature of TES is the application of sensor technology to monitor the product or system whilst in use. When such monitoring solutions are coupled with data transmission technology, we suggest that the signals which result are analogous to KANBAN signals which can be harvested by inventory and logistics support. Baroth et al [114] cite Nissan's "Electronic Concentrated

Controls System (ECCS)" as an early CD Rom based system which harvested data on performance and degradation from which service part requirement could be identified. You et al [82] also cite various leading automotive OEM's and their 1st tier supply chain organisations who are actively developing Remote Diagnostic and Maintenance capability from which triggers for their logistics and supply chains can be initiated. However, You et al also suggest that that the following challenges exist within the auto sector:

- No standardisation between OEM's due to differing data protocols
- The majority of solutions do not include telematics and result in the need to be physically at the service provider (dealerships) to down load the data
- Once the data has been downloaded there is no guarantee that the correct parts (or service skills) are at the location
- Diagnostic Trouble Codes (DTC) are not accurate enough to diagnose product condition at component levels.

Finding 4

*When reviewing **Figure 3,** it is seen that TES covers both hard and soft engineering concepts. In addition the management and business science arena is also significant as such concepts as cost, risk, obsolescence, logistics, governance and strategy are also a focus for study. Communication technology is emerging as being significant as the transmission of product performance and business related data is disseminated across all communication technology platforms and architectures. The increase in this 'connected world' is also giving rise to an increased focus in data and cyber security, the necessity of which is illustrated by continued press coverage (2016/7) of criminal and malicious 'hacking' activities and the emergence of ransomware. As the use of 'connected product support continues to grow its vulnerability becomes of greater concern.*

3.5 Applications of Through-life Engineering Services

There are a wealth of applications of TES reported in the literature. This section is not meant to exhaustively list the different applications of TES but rather provide typical examples where TES have been applied, the industry sectors that appear to benefit from their application, and some uncommon examples of TES solutions that share common characteristics with the main stream of applications.

In the railway sector the most commonly cited application of TES is the maintenance of locomotives and rolling stock. Particular examples include the application of real time monitoring to enable dynamic maintenance scheduling at NedTrain [115], the use of robots in automated train maintenance beyond simple inspection [61] and the extension of the life of London underground trains in the most cost effective manner [85] [116]. From the railway system's perspective various papers citing the work to improve the performance monitoring and measurement systems by utilising data [86] as well as the development of a model to improve the data gathering for more effective initial spare part assortment decision making based on a case study at Netherlands Train [112], offer examples of the future opportunities and challenges.

TES has also been applied in engineering contract design typically including the planning of warranty support. The application of TES in the form of Integrated Product and Service Offering (IPSO) contracts [117] could improve the management of rail infrastructure, optimize maintenance activities and the concurrent design of the PSS contract [106]. This can minimise the risk from inappropriate warranty offerings for both the providers and buyers by subsequent mitigation [118] [119] [120] [121] .

The aerospace sector also has high profile in the citations for TES applications. The emergence of 'power-by-the-hour' by Rolls-Royce and other fleet management programmes [e.g. Boeing [122] [123], General Electric [78], Pratt and Whitney [124]] dominate the discussion. For example, TES has been used to assist in the design for service in a complex Product Service System (PSS) to achieve optimal maintenance cost levels at the earliest stages of conceptual design [125] and to locate and characterize defects and damage of a jet engine's components without having to disassemble it [126].

The automotive sector has long utilised telematics and remote condition-based monitoring especially in Formula 1 cars. By applying similar technologies, Nissan/Renault work to ensure their electric cars have maximum lifespan [127] whilst addressing the low uptake of electric vehicles with focus on cost, range, reliability and availability for use [127] . As the automotive sector continue their design initiatives to supply autonomous vehicles the role of TES is becoming ever more important [128] [129].

Vessel maintenance overshadowed the discussion of TES applications in the marine sector, in particular the elaboration of new approaches for through-life product management with the overall goal to optimise the lifecycle performance of vessels [130]. Extracting and exploiting the information that corresponds to the vessel performance is critical as this can be used to support spare parts contracts [113] in such a way that the objective assessment of costs and benefits across the supply chain can calculated. To achieve this, the roles of key stakeholders during the "in-service phase" will need to be better understood [131], as it can enhance the vessel's the capability.

Other typical applications of TES can be found in the renewable energy and manufacturing sectors. Health and Usage Monitoring are used to improve the maintenance of offshore wind turbine applications [132] [133], where the operations are complex as a result of the harsh environmental conditions [133]. In the manufacturing sector, typical applications of TES can be found in monitoring the condition of machine tools allowing an integration of remote maintenance, global spare parts supply chain and other service offerings [88]. Integrated maintenance service support is also highlighted at a German machine tool manufacturer to help field service technicians as well as administration staff to prepare and conduct maintenance services [54]. This proactive maintenance method is also applied at a flow manufacturing site [134]. The feasibility for TES to monitor materials and component degradation has been trialled in a nuclear power station [135] and TES is also being modelled to illustrate military logistics sustainment [136] and to support the network of complex military satellite systems [137].

Finding 5:

In all industrial applications of TES being reviewed, it was found that they are largely used in the design and operations of high-value complex engineering products with long service life and require continuous maintenance, spanning many industrial sectors, such as aerospace, railway, marine, defence, energy, manufacturing, etc. Management of assets, e.g. building infrastructure, bridges, power station, will therefore be excluded from the analysis. The scope of applications varies from enabling Product-Service System business model to intelligent, predictive maintenance. This finding is aligned to that of Texeira et al [138] *and Tjahjono et al.* [139].

3.6 Features in the effective design of Through-life Engineering Services

In seeking to understand the features for the design and deliverance of TES we sought to identify the enablers and inhibitors for an effective TES from the literature reviewed. Their findings are grouped by themes and are illustrated in (**Figure 5**). Whilst acknowledging that these themes are informed by the key words and search strings applied during the literature search (**Table 1**) it is felt that those applied are generic enough to allow features of TES to be mapped.

It should be noted that during this review there were very few contributions found that studied <u>*directly*</u> the concepts, conditions and situations that inhibited the application of TES, and few papers found that offered examples or case studies of manufacturing organisations who had applied various levels of TES and failed in support of their product offerings. Benedettini et al [100] do report on their research seeking to answer the question "*Why do servitized firms fail?....".* On analysing the data obtained from "75 servitized and 54 non-servitized bankrupted manufacturers……[they]…find the presence of a service business increases overall bankruptcy risk for the supplying firm" [100]. Whilst an association is implied as to cause of failure, no correlation is reported. Benedettini et al classify risks as being either environmental or internal when offering their tabulated 'Impact of the framework factors by firm category' . Of the environmental risks that could be aligned directly to TES when observing this framework, we observe that 'Technological Advance' and 'Impact of Legislation' are identified in Benedettini's study as significant risks. When considering the internal factors which expose the manufacturing organisation to risk they identify the following which could be aligned to TES, (i) inability to restructure (organisation and/or product offering), (ii) high costs of introducing new products or services, (iii) excessive restructuring costs, and (iv) excessive inventory [100].

Benedettini et al’s paper offers the reader a significant insight and contribution by hypothesis of risk to, and explanation for failing ‘servitized’ organisations but does not directly focus on the linkages that could exist between the such companies and the adoption of TES as defined and scoped within this paper. Whilst we believe that there are no doubt commercial failures in this regard from which valuable lessons are to be learnt, they can only surmise as to the negative position. In doing so, we ‘balanced’ the map in (**Figure 5**) by adding a listing of possible inhibitors which should be tested by further research.

The literature is rich in contributions which discuss the role of data, the analysis and systems for handling the data returned from the monitoring of the product, be that ‘in the field’ or from MRO and service support activities. The application of data to effectively conduct diagnostics and prognostics is discussed by Dibsdale [140] during which he offers a taxonomy for MRO support and seeks to align it with Coble & Hines’s [141] classification of prognostic types. However there is an abundance of product performance data available, contributions to the literature discussing data, and journals that specifically focus on data and computing, but it is the need to apply context to get information and subsequently knowledge that is required [142] if such ‘intelligence’ is to be applied in support of the product.

The *‘knowledge management perspective*’ is acknowledged and discussed by Dibsdale [143] when he suggests that “…[Knowledge Management*]..helps manage the risks inherent in products as they increase in complexity, and the organisations and teams who design build operate and support may be dispersed in geography and time*” [143]. Dibsdale discusses the Data, Information, Knowledge, Wisdom (DIKW) model at length and offers insight into the working of the human mind and its implication on knowledge facilitation. He also offers discussion as to the problems that exist relating to codified explicit knowledge exchange, the cultural and technical aspects that support knowledge exchange. We note here that again the focus is on the ‘positive’ with no discussion relative to the negative aspects which could serve as inhibitors to the adoption of TES.

The implementation of any knowledge based management system presents many challenges. Yaeger et al [87] discuss the lessons learned during the process of implementing a knowledge management system into Elekta Ltd, a leading innovator of medical equipment and software. The issues encountered included:

- How to build a knowledge base?
- What is the technology build up and structure of the data-base?
- Information collection
- Information formulation and dissemination
- Information feedback and, monitoring and updating [87]

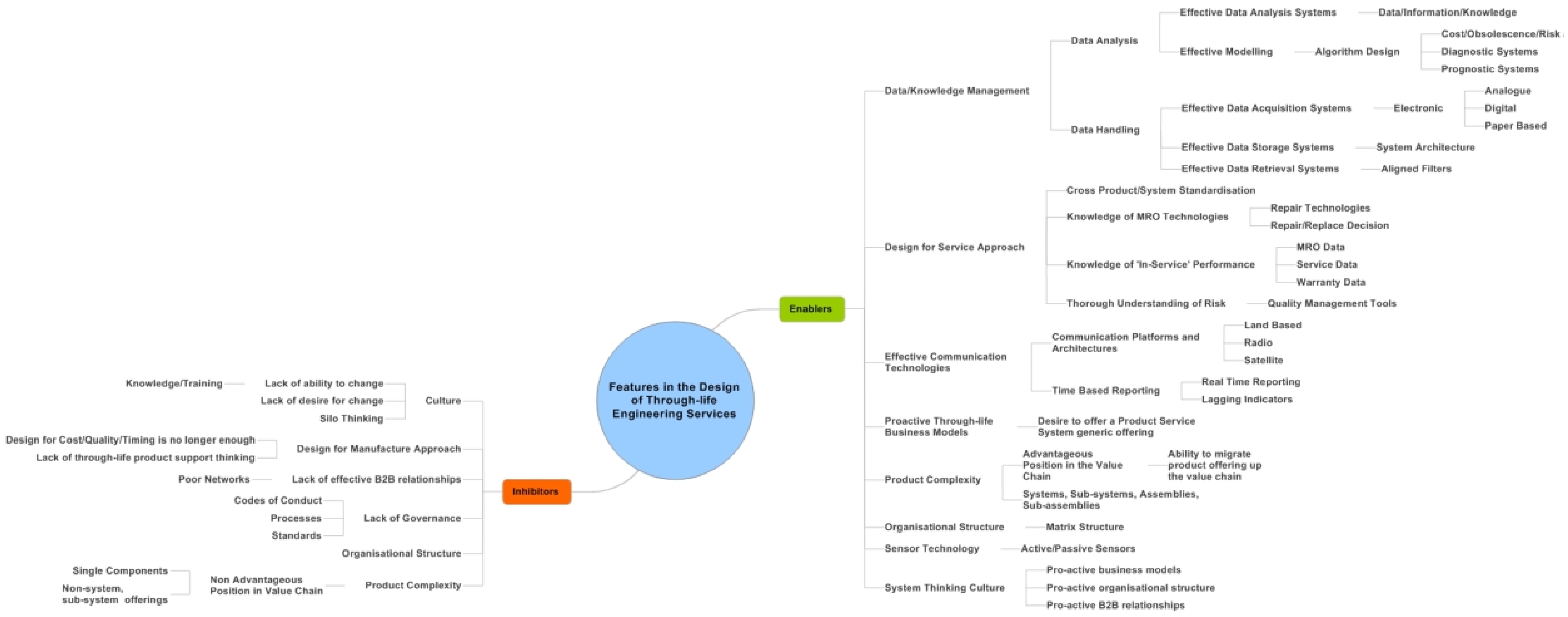

Figure 5: Features in the Design of TES

Examples seeking to address these issues are constantly emerging. McMahon et al [144] [145] discuss the issues experienced in transitioning from information repositories to business knowledge through the exploitation of unstructured data. Their work continues to develop computational tools for the 'exploitation of data collected during operation of the product relative to cost. Their papers focus on the use of 'faceted classification and text mining tools' to allow unstructured data to be exploited whilst Lindstrom et al [59] [57] [58] continue in their work relating to the development and operation of 'Functional Products' as their research continues to develop the means of improving knowledge of availability through the use of service related data.

Whilst the understanding of data within a given context is essential to progressing through the stages of the DIKW model in order to design Lindstrom's 'functional products', we suggest the term '*Informated Products*' is better suited to this study of TES as all product design offers a function by default. To generate knowledge and then forecast remaining useful life through the effective application of diagnostics and prognostics the use of algorithms and simulation models is also a feature of effective system design in TES solutions. The consideration and focus relative to data filters, computational and simulation models in support of TES design and application is well served within the literature and cover numerous aspects and applications. Nonaka et al [37] [146] [147] [146] remain significant contributors reporting on models in support of service and availability for use of machine tools whilst Toossi et al [86], van Dongen [115], Norris [85], Lingegard and Lindahl [117] offer models and the case for their application in the Rail Sectors of the UK, Sweden, and the Netherlands. Upon review it is observed that contributions relating to the generating of models within TES include the calculation of remaining useful life and MRO decisions [148] [149] [150], logistics [151], cost [67] [66] [108], obsolescence [152] [109] [153] and Inventory [151] [154] and all such contributions feature significantly.

When designing products and systems with a view to TES the product or system has to be sufficiently complex enough to warrant the implementation of detailed 'in service' condition monitoring. Such monitoring can take the form of either condition based monitoring through the application of sensors, or the effective recording of service and MRO data which can be workshop or 'field' based. For the data to be of use effective data acquisition, storage, and retrieval systems are required together with well-designed analytical systems that can monitor, diagnose and give forecast as to the Remaining Useful Life informing both operating and service decisions. This requires a 'system approach' to the design, operation, and support of complex engineering products.

Consideration as to how product data is collected or transmitted is also a key feature of advanced TES solutions. Typically the data collection can be manual through the harvesting of traditional records and reports which can be either paper based or digital, stored on their associated medium which can include traditional filing systems requiring manual input into digital storage, or by downloading from on product digital storage facilities examples of which are automotive engine error codes stored within engine management systems. Alternatively, at the more advanced level condition based data can be 'transmitted' as lagging or real time data for subsequent trending and analysis [79] [155] [80] [84]. The literature for the closely aligned TES enabled field of Integrated Vehicle Health Management [156] [77] [157] [158] discusses at length the issues relating to both system engineering in support of the product in use and the transmission of condition and performance data whilst offering developments and guidance to the communication platforms and system architectures which are based upon the need for an 'Open System Architecture' (OSA) [159] [81] to ensure matching of interfaces between adjoining and compatible systems.

This section has presented some of the key features of effective TES support of the product which must be considered by the designer. A system engineering approach with a 'Whole life' bandwidth must be the starting point in product/system design. An understanding of the physics of failure for the system being designed is essential if correct positioning of performance data acquisition sensors are to be correctly located. The means of the acquisition of the condition monitoring data and the timing and frequency of its collection is also significant when designing both the on product and off product supporting architecture. In addition the assessment of Remaining Useful Life (RUL), the means of repair, and the cost of such action when weighed against cost of replacement needs to be clearly understood facilitated by well-engineered decision support frameworks and tools. All these considerations form key features in the effective design of through-life engineering services in support of complex engineering products. It is significant to note that the literature offers no case studies or contribution relating to failed attempts to add and/or integrate bespoke features for TES. In addition there are no contributions which deal with 'doubt' when a manufacturing organisation seeks to move up the value chain through the explicit addition of TES to their product offerings.

Finding 6

*Through-life Engineering Services appear to have differing levels of key features in support of the manufactured product or system. Typically the ability to undertake detailed '**data and knowledge management**' through the application of bespoke algorithms and modelling, appear to be a key element of TES systems. In addition there is a '**design for service**' approach throughout the life-cycle of the product supported (where applicable) by the novel application of '**sensor technology**' for condition monitoring and management purposes. '**Data communication**' also features and is considered in the service architecture which ranges from direct physical downloads to digital transmission communication technologies which can be either land based, Radio, satellite, or a combination of all three. The ability to adopt a TES support solution is heavily dependent on the '**product's complexity**' and requires a '**proactive business model**' which is the product of a '**systems thinking culture**'. Finally the '**organisational structure**' which includes both the internal and external structures and processes have to also be designed and aligned to the organisation's strategic vision for TES.*

3.7 Tools and Methodologies for Designing Through-life Engineering Services

There are numerous tools and techniques relating to the different aspects of the through-life cycle of functional products (i.e. products that are typically sold as integrated solutions), for instance, business models, cost drivers, risks, obsolescence, etc. [160]. These aspects are used to determine the scope of tools and techniques with a particular interest on enhancing decision making, improving maintenance regimes, providing more accurate costing assessments and forecasting as well as modelling the entire processes. This section reviews a range of contributions of tools and techniques that are used in TES.

The consideration for the ease of maintenance of complex products needs to start from the preliminary design stage by detailing a maintainability assessment for the product. At the detailed design stage, the list of predicted maintenance tasks is deliberated [161]. In the context of Maintenance, Repair and Overhaul (MRO), the Fraunhofer Innovation Cluster develops technologies which seek to optimize such MRO processes which include Condition Monitoring and Diagnosis, MRO Planning and Digital Assistance, Cleaning, as well as actual Repair and Overhaul Technologies [162] [54]. Over long periods of operation time, products may change and the MRO service providers (especially non-OEM's) need to keep up with the lifecycle-based documentation. Technologies such as 3D scanning is now used regularly to acquire product data structures more efficiently, to identify parts that have to be maintained, or to determine if spare parts are needed [163].

Modelling is also described in the literature as one of the techniques employed to support maintenance and the through-life engineering of complex products. The reliability of a system can also be effected by the age of components (i.e. usage cycles undertaken) and the number of repairs it has gone through. However, predicting the system reliability, e.g. cumulative number of failures and failure intensity in the future, is difficult. Existing modelling techniques typically utilize Monte Carlo simulations to undertake prediction but this is usually computationally heavy. A new approach of predicting the system reliability employs modified proportional failure intensity models to analyse repairable systems which console aging and repair effects [164]. A key feature in modelling reliability is the ability to virtually accelerate the life of the product as a result of the various operating conditions [165].

Through-life cost modelling is also noted as an important technique supporting TES. A survey was conducted of several companies to better understand costing methods for complex long-life products [107]. The survey identified specific practices useful in developing products to minimise full life cycle target cost. In planning for future TES, it is proposed that the collection of cost data and the understanding of Cost Engineering practices is a potential competitive advantage. A cost modelling technique was also used to reduce expected warranty costs by determining financial losses to all components during the warranty period of avionics products. They considered warranty, reliability and maintenance as key indicators contributing to the minimisation of these losses [108].

The rapid technological advances in component electronics driven by the consumer market are forcing an acceleration in the obsolescence of many components. For sectors employing long life assets such as the defence sector, obsolescence can be costly. Obsolescence management techniques were proposed to mitigate the risks from obsolescence. Furthermore, cost estimation was identified as the key issue in supporting obsolescence management [109].

Finding 7:

There are numerous tools and techniques associated with TES and these are all typically technology-related. For these to enhance decision making and for a company to use them for commercial advantage however, the range of tools and techniques need to include further contribution and understanding in the areas of modelling costs, risk, obsolescence which serve to directly inform management decision processes.

4 Discussion and future research challenges in the development and adoption of Through-life Engineering Services

This paper has presented a literature review which sought to answer five research questions that were defined following a series of workshops and discussions that were attended by invited groups of academics and practitioners. The outcome of the structured review identifies and discusses the content and structure of the contributions directly relating to TES. These include the derivation of a definition for TES (**Section 3.1**), the identification of the structure of the literature relating to it (**Section 3.2**), the requirement for a set of standards for governance (**Section 3.3**), and definition of scope (bandwidth) relating to TES (**Section 3.4**). In conducting this review several industrial applications are identified (**Section 3.5**) together with dissemination of typical features which exist within the in effective design of TES solutions (**Section 3.6**). The tools and methods commonly employed in the delivery of effective design solutions (**Section 3.7**) are also discussed.

However, it is also observed that TES continues to evolve as evermore advanced technical and engineering applications are developed which are both directly relating to, and in parallel with this mode of whole life product support. It is noted that when such technologies evolve they appear to be rapidly assimilated and applied to the area of 'Whole-life' product support.

In conducting this review it has been stated that the literature search has been limited to peer reviewed journal and conference papers and edited books that directly refer to and reference Through-life Engineering Services. It has also been acknowledged that the sources of the literature are centred on a series of Through-life Engineering Conferences and two edited books as they contain the majority of contributions which directly refer to, and align with, TES. Whilst the body of the literature also contains many contributions relating to technology that can enable and support a TES strategy, these were deemed to be out of scope in attempt to set a boundary for the review which was manageable. However, in seeking to identify emerging (and associated parallel but aligned) applications of technology the search strategy does become divergent by necessity, and includes further resources which include media, magazine, and web articles that align with both the search strategy originally defined (**Section 2.2**) and our judgement (informed and subjective) based upon their experience within the field of TES and the technical elements of service support.

In searching and mapping these emergent and parallel 'fields', we identify seven areas which offer the greatest positive potential in the development, effectiveness, and adoption of TES generic support (**Figure 6**). In this section, we also offer subjective (but well informed) opinion relating to the continuing integration of these foci in the development of evolving Through-life Engineering Services.

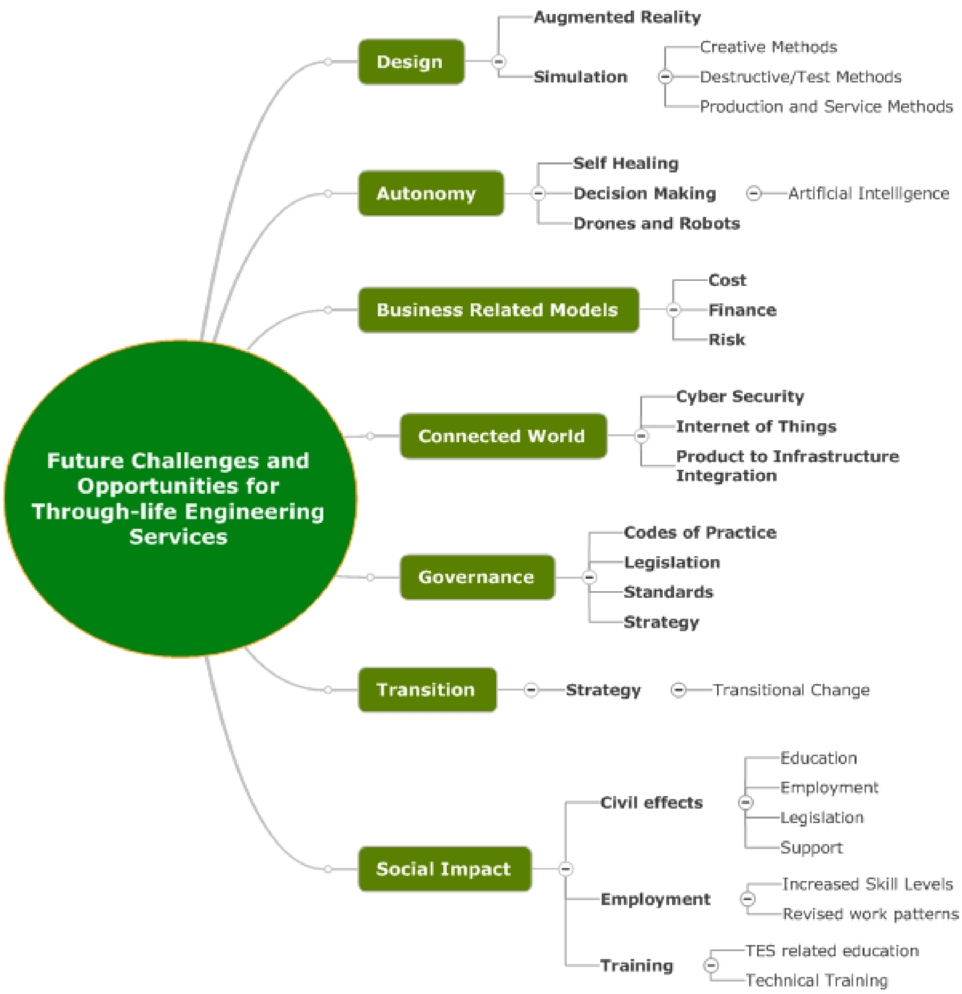

Figure 6: Future Challenges and Opportunities for TES

4.1 Engineering Design and TES

The design of complex engineering products continues to evolve at a rapid rate. It has evolved from the techniques of manual drafting to that of fully integrated computer aided design (CAD) systems supported by simulation packages for virtual test. Typically CAD can form part of a Computer-Aided Engineering (CAE) Platform in support of whole Digital Product Development (DPD) activities which fall within Product Lifecycle Management (PLM) and TES systems. Engineering system design technologies facilitate virtual stress testing of physical parameters and sensor enabled control systems which can then be used to define operating limits. Whilst the literature offers a plethora of contributions for the platform components and subsystems of these digital offerings and applications, we leave the search for information relating to these topics to the initiative of the reader. However, whilst these 'tools' are used in the design of components and systems for TES it is the emergence of 'Augmented Reality' (AR) [166] [167] [168] [169] [170] and 'Virtual Reality' (VR) [171] [172] [173] [174] that offer the greatest potential when designing components, sub-assemblies, systems and sub-systems for use in TES solutions.

Both AR and VR are extremely powerful tools when applied to TES design, practice and application. They both offer the potential to simulate MRO activities which include strip down, diagnostic testing, repair and refit operations. The use of these technologies give the designer, product operator, and service engineer valuable insight when seeking to design for service.

Earliest examples of effective AR were military 'Head UP Displays' (HUD) which give data relevant to important systems in a form which enable the reader of such data to remain focused on 'real world' view-points. The technology is constantly evolving and the display of condition monitoring data and RUL information is also readily available in AR applications. This technology is also evolving to enable portable computing devices to hold both photographs, superimposed CAD data, and system manuals which assists maintenance engineers in the field assess and diagnose products and system faults.

VR technology is used to interrogate design and conduct virtual strip down of complex products. Within the automotive industry for example drive, transmission, and powertrain systems are interrogated to assess the maintainability and access to these complex systems. This can also facilitate placing the design team either inside or outside of the product as they run through such examinations as design for function, design for assembly, design for strip down, design for maintenance, interface analysis, and 'packaging' studies (does the product fit the design space). We suggest that there is great potential to further develop both VR and AR technology so that it can be applied during dynamic simulation of degradation. When conducting degradation analysis it is important to identify and distinguish between primary and secondary failure. Future research in this area using both these technologies would greatly assist in the identification of root cause of failure. Such understanding would aid in identifying the position of sensor technology and its effectiveness thus reducing cost.

4.2 Autonomy within TES systems

Autonomy is gaining increasing significance in the field of TES. Three main areas are identified as emerging at differing rates which include (i) self-healing technologies, (ii) Artificial Intelligence (AI), and (iii) Robotics and Drones. The inclusion of self-healing research and its potential applications which are aligned to TES have been evident from the 1st International Conference for TES in 2012. They have continued to gain significance as both TES and the drive for increasing levels of autonomy grow. McWilliam [63] [64] [175] and Purvis [176] continue to be significant contributors to the self-healing body of knowledge with annual contributions observed between 2012 to 2017. In working towards self-repair of systems, research takes examples from various natural systems and seeks to apply them to industrial applications. Rowlings et al [177] adopts the social behavioural aspects of insects as an inspiration for the design of autonomous self-healing systems for electronic systems in their work relating to 'Networks on Chips' (NoC). These seek to connect large numbers of processing elements by way of 'Nodes' which act as 'distributed colonies' with *"….adaptive controllers responsible for controlling the behaviour of each node (member of the colony), relying only on a set of sensory inputs local to each node….*" [177] to inform an engineering mitigatory response. McWilliam et al [178] [179] [175] continue in their work into resilient electronic system design where the "…*design under evaluation relies upon a novel redundant design strategy intended to provide fault discrimination and selective fault masking embedded within….*" the circuit's Boolean logic.

Farnsworth et al [180] [60] by contrast suggest that the ability of being able to harvest power for use in self-healing in hard to access (or remote) areas is a key enabler for autonomous TES solutions. They suggest that energy harvesting is an essential facilitator and continue in their research using simulation and modelling techniques to investigate the "..coupling…[between]…the mechanical source and the electrical load on the system" [60].

Self-healing and self-mitigation can also include autonomous decision making that is facilitated by Artificial Intelligence (AI). Whilst the search strategy (**Section 2.2**) for this review did not return any contributions for AI *which directly aligned* to TES, we suggest that in the drive for TES which have increasing levels of autonomy the role of AI as a facilitator of 'on system' decision making is self-evident. The use of algorithms to inform decisions relative to remaining useful life (RUL), use or repair, and risk are well documented and we suggest that these are the early evolutionary steps in the journey towards true AI.

The use of Robots and general robotic techniques also have significant roles within delivering TES support. Whilst this literature review has not identified papers that deal directly with this area, the roll of robots in the MRO support of products have value. Farnsworth et al [61] briefly discuss the role of robotics and suggest that "the ability to classify and decompose the main steps and actions involved in undertaking a …..maintenance task….is important" when seeking to use robotic technology in system and component repair. They go on to then inform that the need to link these decomposed tasks (be they physical or cognitive) is essential for robotic solutions. In their discussion they discuss some of the classifications and interactions relating to these issues in support of TES applications. We suggest that there is much potential within the field of cyber physical systems research. One such application is the development of exoskeletons to aid human workers when dealing with heavy loads. Such applications could assist motor function as heavy components are moved whilst ensuring precision of placing.

4.3 Business Models for TES

This review has identified that the research relating to business models is centred upon cost, risk, and obsolescence (**Section 3.4.3**) with no *widely* accepted models and associated tools emerging that can be uniformly applied to organisations seeking to complete through TES enabled product service systems. We suggest that it is significant that there are no contributions that seek to develop and test accountancy rules when seeking to report upon the financial status of organisations who compete through advanced services. Whilst the need for such rules is appears evident by implication as organisations require knowledge of their financial position, they are also required for good Governance and standardisation of reporting.

Whilst not being experts in the field of finance, we suggest that current accounting methods which are required to report on a through-life perspective may be deficient based upon the current search to gain better understanding of cost modelling applicable to TES. One wonders if this lack of detailed understanding could result in non-compliance of widely accepted accountancy rules and are such rules actually valid when seeking reporting of TES enabled availability contracts? What is certain is that governing bodies, the stock exchange, and the revenue are investigating compliance relative to this mode of operation. We suggest that future work relative to defining accountancy rules and regulations in this area is required to fully understand the what is permissible and then mandated by way of good governance through standards within this field.

4.4 The Connected World and TES

The 'connected world' is also becoming a significant enabler for TES. This paper has discussed the transmission of data which can be by land based, radio or satellite systems but the emergence of the Internet of Things (IoT) holds the potential for greater use of on-line monitoring, support and control of products in the environment of use. As the world becomes ever-more connected the issues with 'Big Data' and the security of 'Cyber-Physical Systems for Future Maintenance and Service' [91] offer significant potential for future research. The 'Cloud' is also offering novel ways by which products may be monitored and controlled [162] although there are significant cyber security issues that need to be considered [181].

4.5 Governance and TES

There remains great opportunity and also challenges in defining the systems of Governance when employing TES solutions in support of the complex manufactured product. Whilst there are standards that directly require compliance for the maintenance of complex engineering products (**Section 3.4.4**) the definition and emergence of same for TES is proving to be elusive. This paper has identified the work in this area that is being conducted by the UK-BSI and Cranfield University.

However, there have been no standards, codes of practice, or design rules (advisory or mandated) published which relate directly to TES at the publication date of this paper. A National Strategy for TES [43] has been published which aims to provide impetus in this area. We suggest that further work is required if widely accepted rules for Governance are to be developed and adopted. Such guidance should cover the technical, legislative, financial, dimensions of TES and promote Corporate Social Responsibility for organisations who seek to compete through TES enabled solutions.

4.6 Transition and TES

Resulting from this study and in consideration of a strategy for transition as the manufacturing organisation adopts increasing levels of TES to support servitization, we suggest that the following question naturally arises:

- How does the organisation transition from that of a company having a design and manufacturing offering, Baines's 'Base Level' of operations (**Figure1**), to that of a company which competes through the provision of whole life advanced service offerings which are fully integrated with its manufacturing ability?

We therefore suggest that the key issue here is the definition of the organisation's strategy for change, its formation and execution. Whilst there is an extended body of knowledge within the literature that addresses and discusses both corporate and operating strategies there are no 'bespoke' contributions or documented examples of either successful or failure strategies which seek to deal with this area directly. The closest fit to this requirement is Redding's thesis [25] which offers "*A Strategy Formulation Process for Companies Seeking to Compete Through IVHM Enabled Service Delivery Systems*" but whilst this is a validated and verified contribution, it requires further testing and application before it could be widely adopted. The work that does exist this area is the output of both Neely et al (Cambridge) and Baines et al (Aston) and focuses upon the Product Service System and the servitization process and does not address TES directly. We suggest that such proposed investigations and research should include business, technical, and supply chain strategies. It is also suggested therefore that there is significant opportunity for case study research in these areas of strategy formation directly aligned to TES which would greatly improve the transitional process.

4.7 The Social Considerations relating to TES

The literature offers very little by way of contribution that seeks to deal *directly* with the social effects associated with TES generic applications. The research has illustrated that the application of TES offers greater availability for use of the product's design function which is achieved through effective maintenance and product support strategies. This is of significant importance when considering current trends and views relative to the ownership of products. Driven by a changing environmental and sustainable consciousness one is seeing that there is an emerging desire to purchase the use of the design function of the product rather than the ownership of the product itself. An example of this is in the automotive sector where subscription car sharing is starting to emerge. In this model, cliental purchase a subscription which entitles them to use a car as and when they require to make a journey. They do not own the car and only pay a standard subscription and a metered charge for the journey they do. For the operator of the business model, the reliability of the car fleet and its availability for use if paramount to its financial performance. It is the application of TES generic solutions that serve to mitigate the risk to the operators revenue stream due to breakdown and failure.

Society are also becoming more conscious of their energy footprint as they seek to adopt Smart Metering solutions for the service provision within their offices and homes. Such metering changes the individuals consumer habits as they seek to minimise their expenditure. In addition, advanced metering can, for the supplier of services, monitor the performance of the service supply and also schedule service and MRO activities based upon the frequency and period of use.

When paired with the Internet of Things, TES offers significant potential relative to the connected house in which all applications (fridges, cookers, washing machines, dryers, security systems etc) could be actively monitored and through bespoke monitoring and management algorithms the mean time to failure can be increased or system breakdown possibly eliminated. The potential for future research in these areas in currently endless as society's opinion on product ownership, sustainability and the environment is going through incremental change which in time could result in a paradigm shift in society's behaviour at the macro-level. At the 2017 UK National Manufacturing Debate [182] the increased use of these technologies was recognised and discussed at length by leading academics and senior Industrial Executives. The Chairman of Atkins focussed on the fact that the UK are not training enough engineers, technologists, and scientists to meet the demand for growth in these fields. Whilst a contribution from the Institute of Manufacturing (Cambridge) put forward the spectre of mass unemployment as the rise of automation and increased levels of autonomy continued to transform service support the rise in skilled employment at the technician and professional engineering levels has the potential to be assured.

4.8 Opportunities for further research and contribution

This paper has identified either explicitly or implicitly several opportunities for further research. This section gives a summary of the future opportunities that exist for future research

Table 3 Opportunities for further research

Gap	Description
1	The authors suggest that further work is required to gain a universally accepted definition for Through-life Engineering Services. Of the papers reviewed there was no commonly agreed identity for TES emerging. This paper has attempted to offer a definition that is grounded in the literature identified by this review . The literature offers guidance in this task by stating that a definition should have the dimensions of content, context and purpose in order for any definition to clearly identify the concept under study. This paper has offered an evolution from Redding's [142] first attempt at addressing the problem and it is hoped that future research will build upon these efforts.

2	The majority of contributions to the literature are from academic researchers and closely aligned industrial practitioners. Such contributions look at TES at the macro level, or offer scientific contribution relative to technical areas such as engineering, cost, obsolescence. Greater understanding of TES applications, the advantages and limitations of their adoption is to be gained by the application of case study research. These studies should focus on organisations who are either planning to use, use, or have failed in their efforts to use TES. A comparative review of a significant sample of such case studies whose frameworks are aligned would offer significant insight and understanding relative to TES.
3	Guidance in the formation and formulation of transition strategies for the adoption of TES is also lacking. Typically, how does the manufacturing organisation protect its strategic position in the market place when seeking to adopt TES. At what level should the organisation adopt TES, apply technology to its product offering, and what level of service is the organisation seeking to adopt and can the selected level of TES mitigate any identified risk.
4	There are currently no ISO standards, codes of conduct, or Guidance Notes that explicitly deal with the TES offering. This paper suggests that this could be the result or the lack of a universally accepted definition. Further research should continue with Standards Bodies to develop Governance, Standards, Codes of Conduct, and Guidance for TES.
5	The majority of the literature identified originates in Western Europe, the USA and Japan. Further investigation should be undertaken to identify emergent or existing applications Globally and in particular within other major economies (e.g. Russia, Eastern Europe, Brazil etc)
6	A significant part of the TES solution is the application of sensors and data transmission technologies. A greater understanding of the system architectures that are in use is required. The systems engineering that is implied by Figure 4 needs greater investigation. The authors suggest that there is a need for interface analysis of system boundaries, be they Cyber/Cyber, Cyber/Human in order to understand the system architectures and there interfaces and inter-connectivity.
7	Significant research is suggested in order to understand the business models for organisations within to complete through TES enabled solutions. Typically such questions as what is the optimum cost model arises? How does the company manage its financial decisions when considering capital investment relative to TES? What is the return on investment and when and how is that realised when the TES is used to facilitate the availability contracting strategy. In addition, how does the organisation position its product offering? Clearly the manufacturing company that makes an oil filter casing will not benefit form TES. However, if the product moves to the supply of lubrication systems which also utilise their 'child part' offerings then TES as applied to the system becomes as proposition worthy of study.
8	The application of TES and the monitoring, diagnostics and prognostics potential that the associated technologies have to offer (the prediction of remaining useful life) could be seen as analogous to that of a KANBAN signal. Once this recognition is made it is suggested that TES has

	potential to offer SMART Inventory and logistics in support of MRO activities at service facilities. The authors suggest that there is a direct alignment to the current research relative to Industry 4.0, Logistics 4.0 and this will prove a rich vein for future research.
9	As increasing levels of sensor and communication technology is employed within TES there comes a need for cyber system protection. The authors see convergence between the fields of TES, and Cyber Security as TES enabled strategies and systems evolve.

5 CONCLUDING REMARKS

The aim of this paper was to offer a review of the literature. It is the result of a structured review of both the content and composition of the literature returned is guided by five initial research questions (Section 2.1). Several themes were identified (Figure 3) which informed the structure of this paper with seven findings being reported. The research identifies that there is no widely accepted definition for TES. This paper offers a definition which is grounded in the literature identified with the scope of TES and its content is proposed. Contributions to the literature are seen to originate predominantly from Western Europe, the USA and Japan and from several hot spots based on academic institution and recognised academics working it the TES focus.

The paper identifies significant opportunities for future research in the areas of Governance, standards, codes of practice and guidance notes as TES solutions continue to evolve. Significant challenges in the fields of Business Models, Cost Models, Risk management and Planned Obsolescence are also discussed and identified as having potential for future research. This application of technology in through-life support of the product, and the ability to monitor the product in use offers the potential for novel solutions in the fields of SMART Inventory Management and Logistic Support whilst the increased use of sensors and 'cyber' presents convergence between the research foci of TES, Data Communication, computing and Cyber Security

The seven findings of this review and the eight opportunities (Section 4.8) identified for further research provide a platform to develop further the understanding, generation, and application of knowledge relevant to the TES enabled service delivery system. As manufacturing organisations seek to servitize and adopt Product Service System business models, TES is seen as both a facilitator and risk mitigation solution to the loss of the product's design function and thus loss of revenue. The world is evolving and the emergence of 'Industry 4', the current trend to greater automation and autonomy through increasing levels of data exchange in the manufacturing sector is giving rise to the SMART factory. The development of the Internet of Things, Cyber Physical Solutions and Cloud Computing offer the potential to evolve further Through-life Engineering Services which collectively could revolutionise the mode of manufacture and whole life product support.

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