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Design for Digitally Enabled Industrial Product-Services Systems

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Abstract

Planning the life cycle of industrial product-service systems (IPS2) is highly challenging due to uncertainties experienced in predicting supply (e.g. spares) and demand (e.g. availability) related factors. Whilst digitalisation offers numerous exciting avenues, industry is finding it challenging to realise the potential benefits. This paper focuses on how to design the set of digital technologies and methodologies that serve as enabling capabilities to optimise value across the life cycle. This involves offering a step by step process to compare alternative improvement opportunities (e.g. data modelling, digital twins) with the justification to support investment decisions. The systematic design methodology is tested on an aerospace component, demonstrating the added value of digitally enabled IPS2.

Keywords: Technology prioritisation; design methods; product-service systems

1. Introduction

Through-life engineering services (TES) is a set of tools and techniques, business thinking and network behaviour that enables reliable and predictable improvement of value in-use and enables reliable and predictable reduction of cost in-use for long-life engineering assets [1]. This paper considers TES as an example application of Industrial Product-Service Systems (IPS2). TES has been selected over other IPS2 frameworks (e.g. B2C), as it focuses on a business to business type relationship, where the product (e.g. plane, train, manufacturing facility) itself is typically complex, with a long life cycle. This offers numerous challenges in terms of achieving key targets related to asset availability and costs across the whole life cycle [1]. This involves the integration of products and services to optimise the value from the asset as it evolves over time [2][3]. TES does not only require engineering related practices, as it needs integration in a multi-disciplinary manner across technical and soft capabilities to deliver benefits [4][5]. In order to guide industry to improve the capability and productivity throughout a supply chain, the British Standards Institution published a standard PAS in which a common framework for TES was proposed [2]. Within this framework, four value streams for TES were identified, namely convert, avoid, contain and recover, and are illustrated in Figure 1. The application of each TES value stream can contribute to both providers and customers to achieving the optimal outcomes [2].

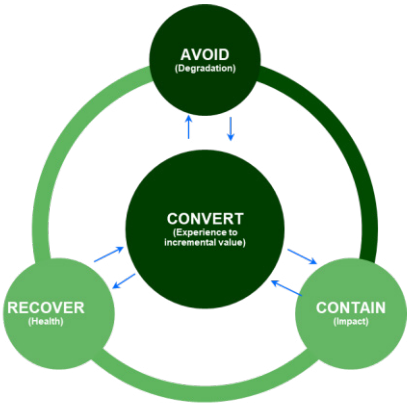

Fig. 1. TES Value streams

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As an overview, “Convert” is the intelligence system that fuels decision making while the other three value streams are the decision and action processes. The value streams are:

Convert: it aims at converting experiences into the incremental benefit through knowledge translation and foresight interpretation [2]. The main activities undertaken include data collection, insight generation and planning.

Avoid: it aims to minimise the physical reality of damage accumulation, by identifying, evaluating and improving drivers or influences of failures and deterioration upfront. Thus, it can be applied to mitigate damages and reduce the potential cost of TES or demand for support interventions in use [2]. Thus, primary activities undertaken include design to optimise through-life value, manufacture with optimum approach and product use within operational specifications.

Contain: during the use of an asset, this stream focuses on mitigating the impact on value and cost from risk of functional failure or potential downtime. This involves interventions in terms of determining the optimum timing and degree of intervention to meet targets [2]. This is achieved by improving predictability, and work-scope specific activities.

Recover: it explains how to restore usable life or inject additional value, considering cascaded decisions that include reusage or rejection, repair or replacement, recycling or disposal [2]. Moreover, relevant resources of system including products, components, spares, services and logistics are determined to achieve customer requirements and value balance. Thus, the activities to be undertaken consist of moving, accessing, inspecting, repairing, replacing and replenishing. Further details on all four value streams are explained in Table 1. From left to right, the figure covers value streams, key options within each value stream to deliver value and lastly it provides an explanation for each option.

Table 1. TES Value streams breakdown

Avoid	**Design**	Design the product to optimise through-life value (operational output / cost of ownership) e.g. maintenance free life, failure modes)
	Manufacture	Manufacture and assemble at the optimum point within allowable tolerances to protect product life in operation and cost of support
	Usage	Use the product within specification and influence operational choices and behaviours to minimising damage / wear and tear accumulation
Contain	**Timing**	Optimise the timing of support activity (inspection, maintenance, retirement)
	Focus	Plan the optimum level of work on the right system ,elements to return best value for investment (e.g. usable life recovered)
Recover	**Move**	Minimise the transportation of products, systems, components and resources in the execution of support activities
	Access	Minimising the number of unnecessary parts and systems touched / disassembled in the execution of targeted maintenance
	Inspect	Inspect based upon need not just opportunity
	Repair	Where parts are rejected employ repair to recover usable life when economically viable
	Replace	Optimise the spares inventory demands and logistics management to minimise stock whilst maximising availability to meet demand
	Replenish	Understand demand and logistics to optimise contracts and pricing for materials, parts, resources and services
Convert	**Data**	Capture and communicate the right data, in the right quantity, at the right point and the right format to provide the fuel to power insight generation and decision support
	Insight	Analyse the data and derive the insight required to power effective operational decision making, risk and opportunity identification and future state prediction
	Plan	Actively convert insight and understanding into recommendations and plans for optimised action

2. Design Framework for Digitally Enabled Industrial Product-Services Systems

2.1. Related work

The number of companies failing in successfully pursuing through-life engineering services is still increasing. Pezzotta et al [6] offer an insight into the suitable business models and delivery processes to deliver service-oriented solutions. Gorschek et al [7] highlight the need for practitioners to influence technology development on the basis of tangible issues identified on site. They develop a step-by-step process for technology transfer. Dobaj et al [8] propose a method for guiding IPSS designers in the specification and implementation of DT instances to serve as the key enablers of IPSS services. Distinct to other research, the gap that this paper focuses on is the process to prioritise and justify use of digital technologies.

2.2. TES delivery

TES aims to increase the in-use value and reduce the in-use cost of long-life engineered assets to the benefit of the user and provider. For example, this could be in the form of increasing the availability, continuous functioning and utility to the user [3]. Whilst there are numerous digital technologies out there, there is a lack of understanding as to how to determine where to use which technologies [9]. Based on 6 hours of interviews and 2 workshops with four organisations from the defence and aerospace industries, we have been able to develop a design framework that offers a structured approach to be able to justify the use of digital technologies. We applied an action research methodology to iteratively evolve the developed process to prioritise technologies. This centred around proposing new technologies in TES and facilitates mapping technology adoption across the life cycle.

Value creation is broken down in to types (e.g. avoid), stages (e.g. data), and the specific areas where change can be made [3]. These are termed as levers. In TES there are five levers that are influential. This means that if you are proposing a new digital technology, it must be able to make an impact across these levers to be able to generate any value. Each of these levers is classified based on three dimensions: “Level, Scale and Location” for each lever were defined. Table 2 includes the details of each of these [10].

Table 2. Descriptions for Support Activity Assets [10]

Item	Descriptions	
Lever Type	People	Different type of people (e.g. skills) required to be able deliver the service and support.
	Spares	The equipment type (ET) level demand for spares.
	Information	Range required to enable complete the service and support requirements
	Test Equipment	Equipment required to be able to diagnose the condition of ET
	Facilities	Facilities required (e.g. hangers) to be able to conduct the maintenance.
Lever dimensions	Level	The different sets of skills
	Scale	The number or quantity
	Location	The physical location

In order to derive value from each of the four streams, there are four stages that need to be followed. If one of these stages does not operate fully, it has knock on effects in terms of achieving the full potential of the value stream. These include: data, insight, plan and act [11]. ‘Data’ is the basis for decision making, and forms the starting point to generate value. ‘Insight’ involves making sense of data, in order to have an understanding of the current or future state of interest. ‘Plan’ involves reviewing the insights gained, and developing meaningful actions to derive value by optimising actions, and outcomes that could be achieved. ‘Act’ involves the process of putting the plans in to action.

2.3. Requirements for digital technologies

In order to clarify the scope of technologies within various contexts, the paper has set three primary goals for developing a list of relevant technologies, and conducted relevant researches based on them, which are explained as following:

(1) Business requirements: considering the business canvas, technologies that can bring substantial return are considered, supplemented by industrial interviews and workshops.

Research Findings: companies prefer to achieve an optimal allocation of levers by considering multiple metrics within their own specific contracts, thus posing challenges for requirement analyses.

(2) Engineering requirements: from a perspective of technology application on engineering solutions, the focused areas are mainly derived from academic literature.

Research Findings: From a review of 50 published research works on digital technologies in TES, the main approaches that have been used are reflected in Figure 2. According to the findings, it is indicated that “Augmented Reality”, “Simulation” and “System Design and Engineering” account a higher proportion, representing a relatively hot focus within the TES context. Though, among emerging technologies, digital twins have received the highest interest.

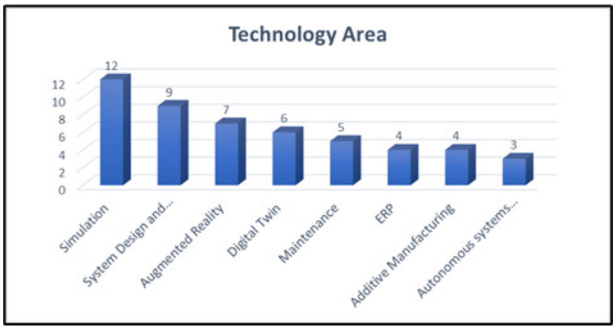


Fig. 2. Engineering View of Technology Focus – literature review

(3) Future requirements: the papers also reviewed the industrial technology roadmaps, which covered promising areas e.g. 5G, Machine learning, Cloud Manufacturing, etc.

Research Findings: with regard to technology roadmaps, the focal points vary as technology development may differ between industries. The Ministry of Defence presented seven foreseeable technology areas to boost considerable opportunities and impacts [12]. In contrast, NASA divided technologies into 9 main sectors, with an overview of technology distributed across sub-sectors [13].

2.4. Value creation opportunities for digital technologies

Based on the literature searches, and the industrial feedback, we have mapped the areas that alternative priority technologies can add value in TES, as illustrated in Table 3.

Table 3. Digital technology application areas

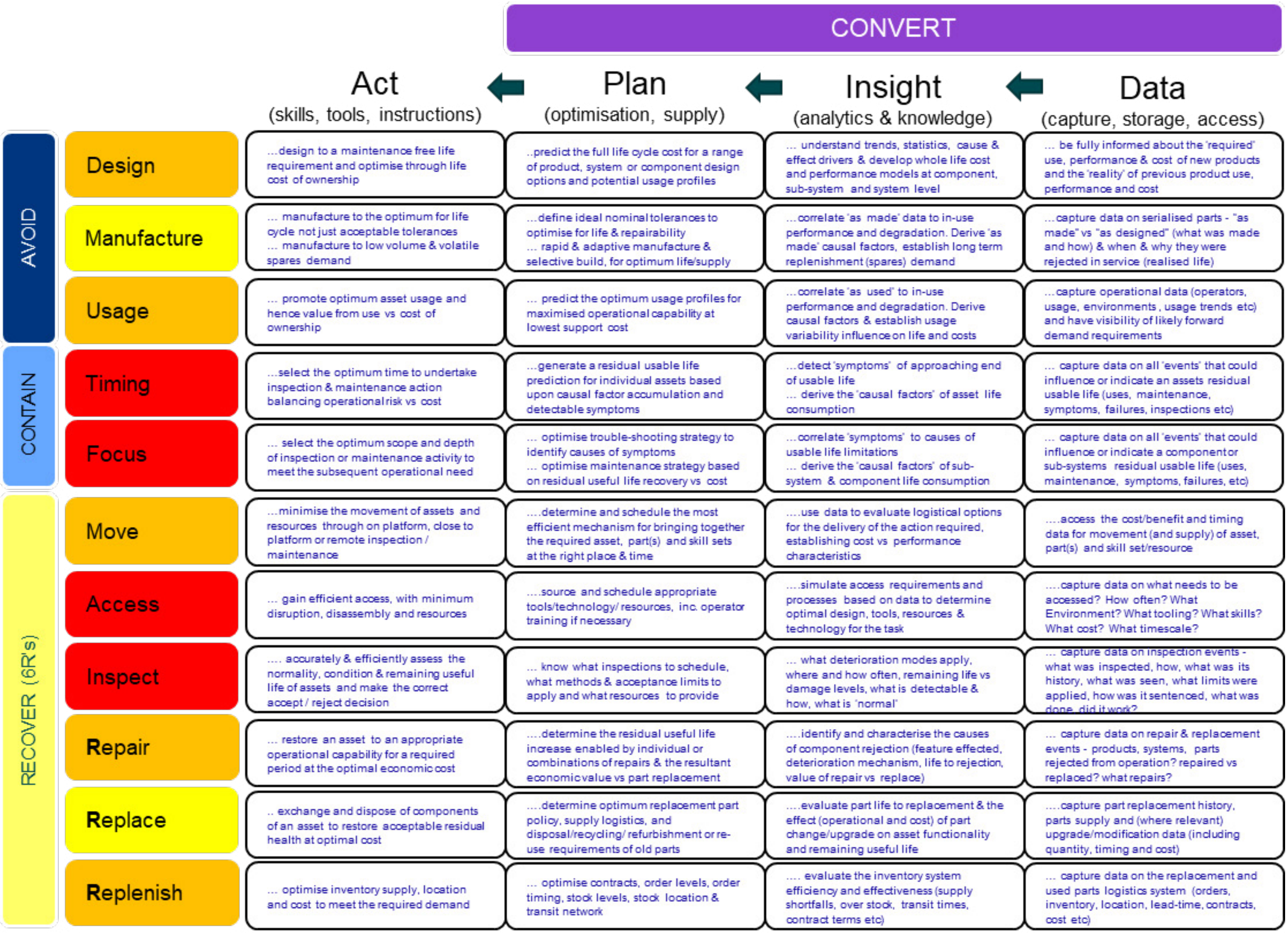
Technology	**Application**
AR/VR **Advanced Visualisation** **Digital Work Instructions**	Training AR work instructions (e.g. for maintenance) Remote support Visualising deterioration Visualising deviation from nominal data AR/VR H&S Dynamic risk assessment
Robotics **Automation** **AGVs**	Invasive robotics
Metrology and automated inspection	In-line/in-process inspection Portable/in-field/in-situ inspection
Additive manufacturing	Design for X In-service modification Portable manufacturing/repair systems
Cyber security	Data storage & transfer Systems architecture
Sensors, IoT, and cloud	Sensor embedment Data capture In-service data Condition based monitoring 5G
AI and machine learning	Design for X Understanding degradation
Digital twins and simulation	Topology optimisation Usage simulation Discrete event simulation Maintenance scheduling Operational / life cycle simulation

Based on the interviews and workshops that we held, we were able to deduce a process as to how organization’s consider value, and how it is important to map individual and collective digital technologies to the specific value streams. It was observed that this was not done systematically, and consistently across organization’s, which demonstrated the need for the design framework that is presented in this paper.

2.5. Proposed design framework digital technology use

The proposed design framework is aiming to develop a systematic way to determine how to derive value from digital technologies for any given complex asset or process, as illustrated in Figure 3. In the framework, Step 1 (value drivers) focuses on determining what drives value. This involves prioritising the main sources of value creation (“avoid”, “contain”, “recover” and “convert”).

Step 2 (value creation stages) focuses on determining the stages involved in creating value. As an example, in the TES context these are: data, insight, plan and act, which were explained in Section 2. Each of these areas can have a direct impact on value creation. Although, these are generic and can be applied across Industrial Product Service Systems, the specific context will influence in more detail how the value can be created. Thus, it is recommended to take a multi-disciplinary approach to collate ideas across numerous functional teams to populate the proposed framework. The important outcome from Step 2 is to provide an architecture for being able to compare the alternative improvement options.



			CONVERT		
		Act (skills, tools, instructions)	Plan (optimisation, supply)	Insight (analytics & knowledge)	Data (capture, storage, access)
AVOID	Design	...design to a maintenance free life requirement and optimise through life cost of ownership	..predict the full life cycle cost for a range of product, system or component design options and potential usage profiles	... understand trends, statistics, cause & effect drivers & develop whole life cost and performance models at component, sub-system and system level	... be fully informed about the 'required' use, performance & cost of new products and the 'reality' of previous product use, performance and cost
	Manufacture	... manufacture to the optimum for life cycle not just acceptable tolerances ... manufacture to low volume & volatile spares demand	...define ideal nominal tolerances to optimise for life & repairability ... rapid & adaptive manufacture & selective build, for optimum life/supply	...correlate 'as made' data to in-use performance and degradation. Derive 'as made' causal factors, establish long term replenishment (spares) demand	...capture data on serialised parts - "as made" vs "as designed" (what was made and how) & when & why they were rejected in service (realised life)
	Usage	... promote optimum asset usage and hence value from use vs cost of ownership	... predict the optimum usage profiles for maximised operational capability at lowest support cost	...correlate 'as used' to in-use performance and degradation. Derive causal factors & establish usage variability influence on life and costs	...capture operational data (operators, usage, environments , usage trends etc) and have visibility of likely forward demand requirements
CONTAIN	Timing	...select the optimum time to undertake inspection & maintenance action balancing operational risk vs cost	...generate a residual usable life prediction for individual assets based upon causal factor accumulation and detectable symptoms	...detect 'symptoms' of approaching end of usable life ... derive the 'causal factors' of asset life consumption	... capture data on all 'events' that could influence or indicate an assets residual usable life (uses, maintenance, symptoms, failures, inspections etc)
	Focus	... select the optimum scope and depth of inspection or maintenance activity to meet the subsequent operational need	... optimise trouble-shooting strategy to identify causes of symptoms ... optimise maintenance strategy based on residual useful life recovery vs cost	...correlate 'symptoms' to causes of usable life limitations ... derive the 'causal factors' of sub-system & component life consumption	... capture data on all 'events' that could influence or indicate a component or sub-systems residual usable life (uses, maintenance, symptoms, failures, etc)
RECOVER (6R's)	Move	...minimise the movement of assets and resources through on platform, close to platform or remote inspection / maintenance	....determine and schedule the most efficient mechanism for bringing together the required asset, part(s) and skill sets at the right place & time	....use data to evaluate logistical options for the delivery of the action required, establishing cost vs performance characteristics	....access the cost/benefit and timing data for movement (and supply) of asset, part(s) and skill set/resource
	Access	... gain efficient access, with minimum disruption, disassembly and resources	....source and schedule appropriate tools/technology/ resources, inc. operator training if necessary	....simulate access requirements and processes based on data to determine optimal design, tools, resources & technology for the task	....capture data on what needs to be accessed? How often? What Environment? What tooling? What skills? What cost? What timescale?
	Inspect	.... accurately & efficiently assess the normality, condition & remaining useful life of assets and make the correct accept / reject decision	... know what inspections to schedule, what methods & acceptance limits to apply and what resources to provide	... what deterioration modes apply, where and how often, remaining life vs damage levels, what is detectable & how, what is 'normal'	... capture data on inspection events - what was inspected, how, what was its history, what was seen, what limits were applied, how was it sentenced, what was done, did it work?
	Repair	... restore an asset to an appropriate operational capability for a required period at the optimal economic cost	....determine the residual useful life increase enabled by individual or combinations of repairs & the resultant economic value vs part replacement	....identify and characterise the causes of component rejection (feature effected, deterioration mechanism, life to rejection, value of repair vs replace)	... capture data on repair & replacement events - products, systems, parts rejected from operation? repaired vs replaced? what repairs?
	Replace	.. exchange and dispose of components of an asset to restore acceptable residual health at optimal cost	....determine optimum replacement part policy, supply logistics, and disposal/recycling/ refurbishment or re-use requirements of old parts	....evaluate part life to replacement & the effect (operational and cost) of part change/upgrade on asset functionality and remaining useful life	....capture part replacement history, parts supply and (where relevant) upgrade/modification data (including quantity, timing and cost)
	Replenish	... optimise inventory supply, location and cost to meet the required demand	... optimise contracts, order levels, order timing, stock levels, stock location & transit network	.... evaluate the inventory system efficiency and effectiveness (supply shortfalls, over stock, transit times, contract terms etc)	... capture data on the replacement and used parts logistics system (orders, inventory, location, lead-time, contracts, cost etc)

Fig. 3. Design framework for digital technology justification

In Step 3 (value prioritisation), the framework requires a detailed analysis of where the real improvement opportunities lie. The value stages from Step 2 are used to structure the improvement opportunities. In this step, the first task is to delve into which value creation stages need to be prioritised. Thereafter, it involves proposing improvement opportunities, and populating ideas holistically across the priority areas to be able to compare where the nominal improvement will make a higher impact in the timescales that matter. This also recognises the fact that there will be limited budget for improvements, and hence a prioritisation is needed to allocate the budget in the right area(s), rather than trying to allocate funds across the whole framework, as shown in Figure 7. Step 3 ends with defining the requirement(s) for what a technology should do to create value.

In Step 4 (technological specification), a detailed analysis takes place to determine which specific technologies can actually make a reasonable impact. This initially involves developing a feasible set of technological options as aligned to the value creation stages, and the prioritised areas. The list of technologies is not fixed and depends on the priorities identified within the specific context. An example list of technologies is provided in Figure 6. In Step 4, the list of technologies is compared based on alternative metrics such as maturity in technology, organisational culture for adoption, return on investment, skills requirements, and timeliness. As part of this paper, the scope of the paper is limited to being able to position relevant technologies to be able to derive value. The prioritisation across the technologies is considered to be out of scope and will form our future work. However, work to specifically prioritise in terms of return on investment was covered in previous research such as [8] [14]. Section 3 covers a detailed example of applying the proposed framework.

3. Case study: HP turbines

The case study utilised is in the context of HP turbine for jet engines. Whilst, modern turbine blades are comprised of special high temperature nickel alloys, they often suffer from gas temperatures that go beyond their melting point. For the jet engine, there are three primary factors that affect the thermal efficiency [15]: turbine inlet temperature, compression ratio, and the component efficiencies of the compressor and turbine. To illustrate the challenge, hot gas path is capable of getting so hot that the gas literally softens and melts metal. In terms of the implications for through-life considerations, high temperature corrosion and oxidation of the gas turbine material are common, which significantly affect the life of turbines. Particularly heavy fuels contain several aggressive corrosion elements such as sodium, potassium, lead and vanadium which cause corrosion of the hot gas path components. There is also a major challenge with how to trade off performance demands against the high thermal, mechanical and aerodynamic loads placed on the turbine parts. This background to the case study aims to demonstrate that there are numerous improvement needs, however, it is not so straightforward to design digital technologies aligned to value creation opportunities with a vast range of options available. The following provides an overview of how the proposed design framework was applied to HP turbines in collaboration through interviews with a major jet engine manufacturer.

Step 1 (value drivers): it was decided that the value drivers would be "avoid", "contain", "recover" and "convert" because they offer a comprehensive landscape to apply through-life considerations within the context of HP turbines.
Step 2 (value creation stages): when designing HP turbines there is a common series of value creation stages across their life cycle, which includes - data, insight, plan and act.
Step 3 (value prioritisation): this included the technological requirements capture broken down based on the prioritised value drivers and value creation stages. Here the initial task was to evaluate where the highest value creating opportunity existed. Based on the value drivers the highest potential for improvement was considered to be 'avoid'. This was because the case study had the priority to reduce the impact of corrosion and oxidation, as it was having a significant impact on maintenance requirements. With the case study being offered in contracts involving performance-based outcomes, the increase in maintenance requirements means the solution provider loses revenues and profit. The following demonstrates the key considerations and requirements for the value creation stages in the context of 'avoid' for HP turbines:

Data:

- Data is needed in the following areas: What is the scope of the turbine? What should the turbine be capable of? How was the turbine manufactured? When was the turbine installed? How was the turbine used? What have we done to the turbine (inspected, repaired, replaced)? What did each activity cost? How much was the turbine used? What output did the turbine produce? Did the turbine work as expected? What disruption did it cause? What was the turbine exposed to? Any market benchmarking/feedback?
- Data needs consider capabilities in terms of: sensing, transmission, storage, security, search, accessibility, trading, generation, sharing, cleansing and quality.

Insight:

- Insight is needed through historical records, e.g. what have we experienced in terms of failures and degradation? how much where and when?
- Apply methods: to classify and cluster images to be able to recognise patterns, quantify and rank occurrences, context mapping (e.g timelines, geography, people), anomaly and trend spotting, causality mapping, tacit knowledge capture and sharing, context comparison including current design vs past operational experience.

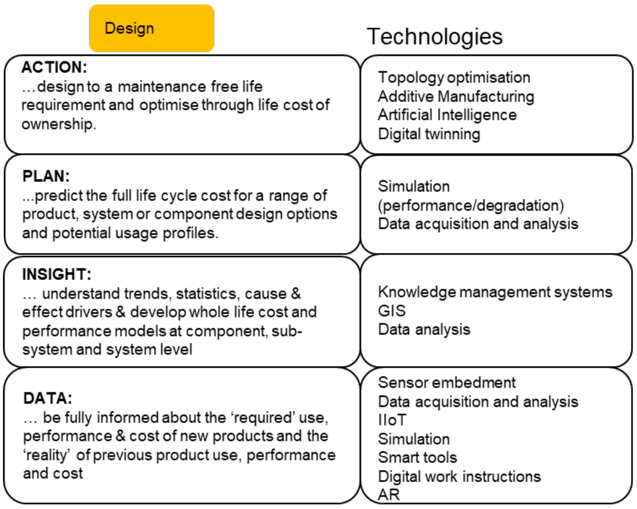
Plan:

- Apply predictions in terms of: operational usage considering the expected scope of use, through-life attributes (e.g. safety, reliability, maintenance free life, etc.), through-life deterioration and maintenance activities, and the cost.
- Develop the optimised design plan including opportunities for automation of design based on safety, reliability, maintenance, cost, etc.

Action:

- Apply methods considering: design for safety, reliability, maintenance free life, inspect-ability/monitorability, accessibility, repair, upgrade/update/replacement and disposal/recycling/reallocation. This is where the most suitable method(s) are compared and prioritised for use.
- Involves capturing feedback to enable continuous improvement and informing the other value creation stages. The feedback can be elicited formally and informally in terms of statistical and subjective feedback. 'Action' will offer ways to collect the feedback continuously over time.

Step 4 (technological specification): based on the considerations and requirements set out in Step 3, here we identify the relevant set of technologies across the value creation stages. Once the list of technologies is identified, it is necessary to decide which area(s), if not all, will the specific investment be made in to seize the value creation opportunities. Figure 4 illustrates the list of technologies that have been proposed for 'avoid' based value creation for HP turbines. Due to the page limits, only results for 'design' are presented, but the case study analysis covered the life cycle.



Design	Technologies
ACTION: …design to a maintenance free life requirement and optimise through life cost of ownership.	Topology optimisation Additive Manufacturing Artificial Intelligence Digital twinning
PLAN: …predict the full life cycle cost for a range of product, system or component design options and potential usage profiles.	Simulation (performance/degradation) Data acquisition and analysis
INSIGHT: … understand trends, statistics, cause & effect drivers & develop whole life cost and performance models at component, sub-system and system level	Knowledge management systems GIS Data analysis
DATA: … be fully informed about the 'required' use, performance & cost of new products and the 'reality' of previous product use, performance and cost	Sensor embedment Data acquisition and analysis IIoT Simulation Smart tools Digital work instructions AR

Fig. 4. Design focused technology propositions for turbine blades.

Here we specifically focused on 'design', because it was considered to be the priority for the sponsor given the early stages of the life cycle in which they can make significant impact across the life cycle. The identification of technologies should be made in a multi-disciplinary manner and it is worth evaluating these regularly.

3.1. Example technology: Digital twin

From the technologies identified, a strong level of interest was captured for applying digital twin technologies to improve ‘design’ considerations. Given that digital twin technologies require the two-way communication between the physical asset and its digital representation, the focus on design was to create the architecture that would enable the implementation of digital twins in the following phases of the asset life-cycle [16]. Digital twin technologies were considered particularly in the context of ‘act’ in order to enable a maintenance free life. It is also worth mentioning that there is an assumption that we capture, store and access the right data, analyse it effectively to extract the right insights and, hence, make the right plan. All the knowledge obtained from convert can be then used to implement ‘act’ properly. Here the design of the digital twin requires in depth consideration of its sophistication from the perspective of what depth and range of analyses will be offered based on the decisional requirements. This will address the question on how far does it go in terms of answering critical questions. Along with that, it will also be important to consider the targeted level of maturity for the digital twin in terms of how ‘well’ the system achieves its requirements. So, by applying the proposed framework, it is possible to design a digital solution with a value creating impact.

4. Discussion and conclusions

As the importance of innovation through emerging technologies becomes more vital than ever before, the decision-making process to prioritise various technologies within distinct contexts is becoming more complex. This is linked to numerous conflicting targets across strategic, operational and tactical dimensions, which make the decision-making process for value optimisation very challenging. Based on a series of interviews and workshops with practitioners, it has been realised that digital technology selection is currently conducted in a subjective way due to a lack of reliable evidence-based approaches.

This paper offers insights into a systematic design framework to map out digital technologies within the context of Industrial Product Service Systems. The framework is particularly aimed at filling research gaps in ‘design methods’ for aligning digital technologies to create value across the life cycle of complex engineered assets. This means that the proposed framework can help to fulfil the potential offered from digital technologies with targeted value creation, which is missing in related work as noted in Section 2.1. The proposed framework has only been tested within a through-life engineering context, so the results are currently limited.

The framework recognises that digital technologies are dynamic and constantly evolving both in terms of capabilities, and the range of options that are available. The proposed framework does not promote a fixed range of technological options, but instead, it promotes organisations to design the best approach(es) to utilise digital technologies. It is a highly flexible, and modular approach to align value creation to digitalisation. From a design perspective, the novelty here is from two aspects. Firstly, it builds effectiveness considerations in to design in terms of how digital technologies can increase the value derived from an activity within the through-life engineering services landscape (including enabling new activities not achievable without new or improved technology). Secondly, it enables to decrease the costs and resources required to deliver the activity value (including making currently uneconomic activities viable).

There is future work needed to be able to capture a breakdown of the through-life engineering services implementation landscape. This includes deciding where to use which digital technologies for realising future high value improvements. There is also a need to develop approaches to be able to qualitatively and quantitatively evaluate numerous multi-disciplinary metrics in the process of prioritising digital technologies over alternative timeframes.

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