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Future-proofing the Through-life Engineering Service Systems

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Abstract

Future-proofing through-life engineering service systems (TESS) is crucial for ensuring their reliable, long and economical whole lives. The TESS are typically composed of high value industrial products and engineering services organised around them. Future-proofing can broadly be achieved by enabling disruption and change management capabilities. However, understanding of TESS future-proofing is limited, which is also important due to the recent industry 4.0 advancements. This paper contributes by presenting (1) a concept of TESS future-proofing, (2) a framework of TESS future-proofing, and (3) examples of the framework application at: (i) management level via change prediction method (CPM), and (ii) operational level via industrial augmented reality (AR).

Keywords: Future-proofing; Through-life Engineering Service Systems; TESS; Industrial Augmented Reality; AR; Resilince; Disruption Management; Change Prediction; Change Management

1. Introduction

Future-proofing has been defined as "the process of anticipating the distant future and taking actions to minimize risks and maximize opportunities for value realization from assets through its planning, design, construction, operation and maintenance processes" [1, 2, 3]. Essentially, future-proofing involves the consideration and management of future

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disruptions and changes. Future-proofing has also been used in terms of re-configurability [4], obsolescence management [5, 6], long-term business continuity [7], long-term information continuity, and digital preservation [8, 9].

The TESS future-proofing can be defined as "the process of anticipating the future and taking actions to understand and manage future disruptions and changes that impact on TESS planning, design, manufacturing, operation, maintenance and support processes". Essentially, TESS future-proofing involves the consideration of future disruptions in the production management systems of the enterprise as well as change management across product architecture, in-house production and external supply chain.

The TESS community has focused on following topics amongst others most recently: applications of VR and AR, railway industry, jet engine regeneration, life extension and repair, internet of things (IoT), maintenance informatics, condition based and predictive maintenance, product service systems, solutions to the impact on availability and cost, and electronics [10]. However, understanding of TESS future-proofing has been limited but is important because of its potential of increasing operation and service life, sustainability, and reduced whole life cost to name a few. Therefore, the main aim of this paper is to understand how to future-proof TESS.

The rest of the paper is organized as following. A framework of future-proofing TESS is proposed in section 2. The TESS future-proofing using CPM (at strategic level), and industrial AR (at operational level) are presented in section 3. Conclusions are presented in section 4.

2. Framework of future-proofing TESS

A framework of future-proofing TESS is proposed in Fig. 1. The framework is composed of a top level aim in terms of future-proofing TESS, a set of criteria as will be discussed here, a pre-requisite of (big) data-information-knowledge-decision making [11] which is crucial in order to fulfil the future-proofing criteria in context of implementation levels of management and operations to consider.

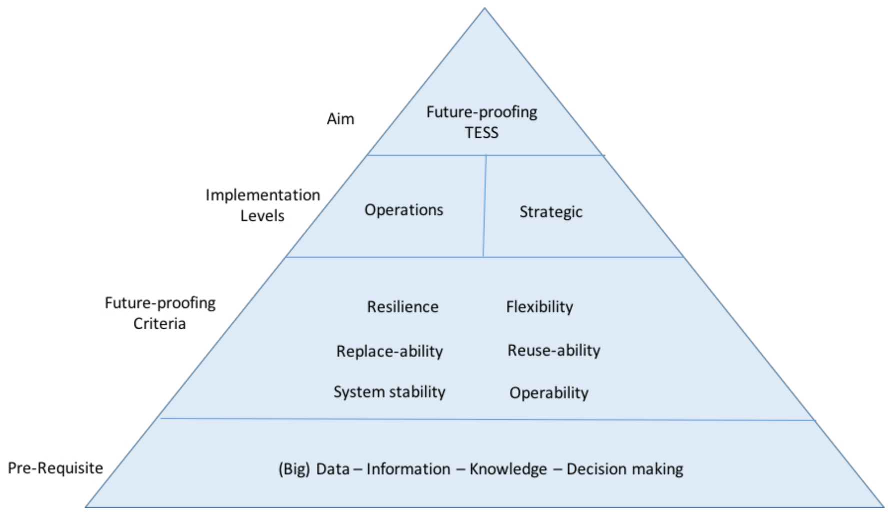

Fig. 1. The Framework of Future-proofing TESS.

Following criteria are proposed as a means of assessing the ability of key TESS to cope with future disruptions and changes based on [1, 12]:

- Resilience - the ability of the TESS to withstand shocks and recover quickly.
- Flexibility - the ability of TESS to readily adapt or reconfigure if understanding of risks or requirements change over time.
- Replace-ability - the ability to be replaced during or at the end of TESS life or use, assuming that those have finite lives.

- Reusability - the ability of the TESS to be reused or extended at the end of their lives. Even though extension is partially used in adaptability as well it is executed during operation phase there while in reusability, extension is meant to be at the end of life.
- Operability / Information future-proofing – the ability of TESS to be operated over their lifecycle. Information future-proofing is an important part of operability, and it is especially important for decision makers, for a 'system of systems' view, for future owners, operators, the environment and society [1]. Hence, it is important to identify through-life information requirements at earlier life cycle stages of TESS and future-proof information at all stages via planning and taking appropriate actions for its collection, retention and reuse in long term [1, 13].
- System-stability - the ability of TESS to work for an overall balanced or positive effect, ensuring stability of a system or systems during or after change(s) or disruption(s) in the system. This could also mean that systems should work with rather against natural processes [14].

The definition of future-proofing is applicable to a wide scope of TESS including transport, energy, water and communication services. However, the case studies presented in this paper were selected to provide examples at both management and operations levels while also considering the industry 4.0 advancements. Hence, based upon this and because of the nature of the organisations engaged in both case studies, this paper provides more focus on automotive sector.

3. Strategic Level TESS Future-proofing via CPM

The strategic level TESS future-proofing can be executed via CPM. The change management domain focuses on the task of adapting an already established system. These adaptions could be engineering changes (EC), which are adaptions of the structure, behaviour, or function of released products [15], or manufacturing changes (MC), which are adaptions of a factory system and its elements [16]. These changes could occur throughout the entire product lifecycle and are triggered either by problems or by advancements of products and processes [17]. Thus, as companies become more multi-disciplinary and face shorter product lifecycles, it becomes a competitive advantage for them to effectively and efficiently handle changes.

The key challenge of change management is that instigating changes could propagate and cause further changes throughout the system (change propagation) due to the various dependencies within a system [17]. Thus, change management aims to proactively reduce the system dependencies and to reactively control and handle the system dependencies during a change [18].

3.1 Change Assessment / Management Methods

A key enabler for change management are assessment methods that quantify the impact of a change to support proactive and reactive decision-making [19]. In literature, a variety of change assessment methods are discussed. A variety of methodologies are used to model and assess the impact of changes. Examples for this are Bayesian Networks [20], mathematical models [21], and design structured matrix models [22, 23, 24]. One of the most established assessment methods is the change prediction method (CPM) [19]. The assessment scope of most methods is limited to dependencies within the product architecture (PA). These methods only vary in the level of detail and types of dependencies that are considered within the product architecture domain. Some methods break the PA down into components [17], whereas other methods describe the PA with more details, such as at a functional, behavioural, and structural levels [25] or even at a product parameter level [26]. Also, some papers exist that assess the impact of changes within the manufacturing domain [16].

However, not many papers exist that capture dependencies and assess changes from multiple perspectives. For example, Rouibah and Caskey [27] captured the dependencies between design and manufacturing parameters and considered its responsibilities, such as in-house, supplier, or engineering partner. A gap highlighted by various researchers is that assessment methods do not sufficiently consider the propagation of ECs into the domain of manufacturing processes and the supply chain [15, 16, 28]. Furthermore, the relevance that changes should be assessed from multiple domains can be seen in EC methods that support the workflow of ECs along the entire value chain [29] and the literature on three-dimensional concurrent engineering [30].

In recent research, this gap was addressed to improve decision making in change management. The objective is to extend EC assessment methods with a value chain perspective. One recent research project was about linking the product components of an off-site manufacturing building with the supplier selection criteria for each component [31]. However, further case studies on different perspectives are still needed, for example with a value chain perspective.

3.2. Value Chain CPM – Cases from the Automotive Industry

In a recent research project, three cases were conducted in the automotive industry that aimed to verify the Value Chain CPM (VC-CPM) (see Fig. 2.), which is an extension of the PA-oriented CPMs from literature. The core of the VC-CPM is formed by the PA domain that captures the topological dependencies between the product components. Compared to the PA-oriented CPMs, the VC-CPM additionally embraces a domain for manufacturing processes (MP) and assembly processes (AP). The purpose of the MP and AP domains is to capture the topological dependencies between the components and their related processes considering all process-related resources, such as tooling, equipment, and sub-supplier parts. Furthermore, these domains capture the split between in-house and supplier processes.

The cases from the automotive industry (focussed on the door trim panel) demonstrated the contribution of the VC-CPM to the future-proofing at a management level:

- *Flexibility, Reusability, and Replace-ability* - During the pre-series phase, car manufacturers often adapt their products and processes due to design errors or low process capabilities. Also, products and processes are often replaced due to new customer requirements or more efficient process technologies. Based on the VC-CPM areas in the product and processes could be identified that are highly dependent on each other. This information supports decision-making about where to decouple products in the PA or where to create more changeable processes. For instance, the VC-CPM of the door trim panel showed that the carrier is highly coupled to the other components of the PA. Furthermore, most of these components have highly dependent MP. Thus, for instance, a change in the carrier, could affect a change in the door and its MP (see Fig. 2. (a).). Now, a decision that could be made to increase the changeability of the system is whether to aim for a more modular product architecture to decouple the carrier from the other components or to aim for more changeable manufacturing process so that the processes do not have to be changed with each product redesign (see Fig. 2. (b) and corresponding labelled areas in (a)).

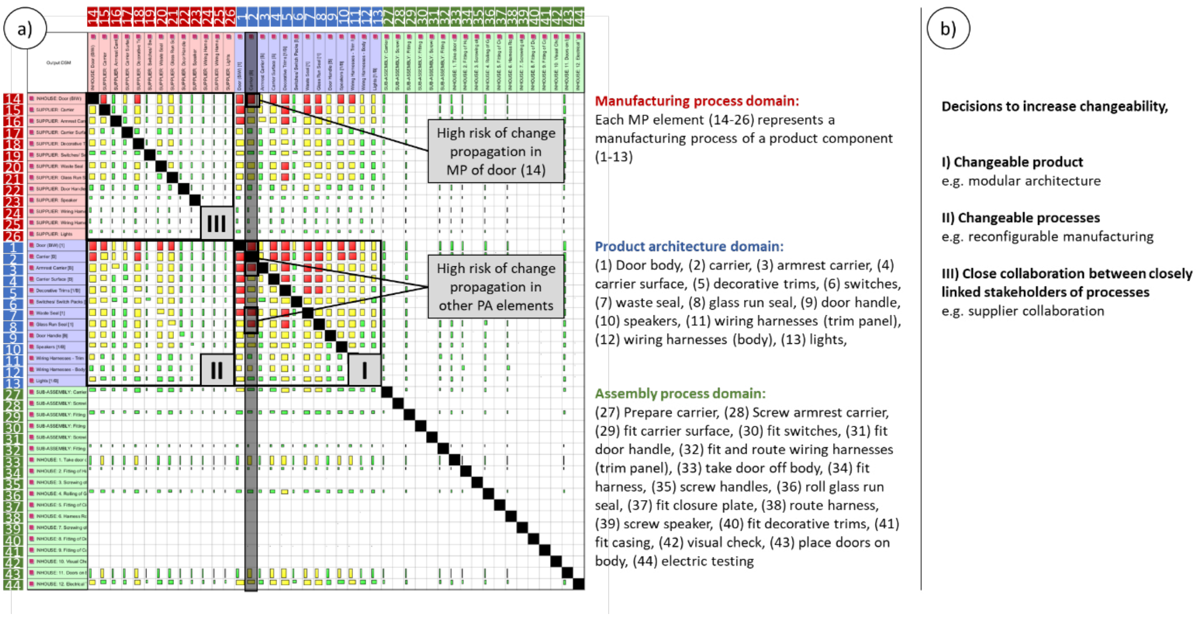

Fig. 2. (a) Change prediction - Example of a change in a door carrier highlighted; (b) Decisions to increase adaptability and replace-ability.

- *System-stability and Resilience* - Another complexity that occurs with changes is the risk that stable processes and a stable product quality could not be met anymore. The case companies emphasised that they aimed to prevent changes in components that have many customer relevant requirements, such as the handle that embraces optical and functional requirements. Furthermore, they also aimed to prevent manufacturing changes that might have affected unexperienced or critical suppliers. Thus, the VC-CPM allows to evaluate which areas might be affected by a change to prevent changes in critical areas and to ensure a system-stability.
- *Operability / Information future-proofing* - A pre-requisite to profit from the VC-CPM is to capture the information about the elements that should be reflected in the system and the information about the direct change relationships between these elements. This information must be captured from a variety of stakeholders within and between different departments (e.g. engineering, production planning, purchasing, supplier management). A challenge is to ensure up-to-date information. However, the VC-CPM can also be seen as a management tool that improves communication between different stakeholders. Once the initial VC-CPM is created, updates in the process and product specification can easily be captured due to the user-friendly applicability of the CPM model.

4. Operational Level TESS Future-proofing via Industrial AR

The operational level TESS future-proofing can be done via industry 4.0 technologies. For example, industrial AR is a central part of Industry 4.0 concepts [32]. It provides workers with access to digital information by overlaying information with the physical world. AR is positioned between a complete virtual reality (VR) and the physical reality [33]. Due to AR merging the virtual and the physical world, it facilitates the interaction between humans and the available digital content. Hence, the possible applications of AR in an industrial context are broad and reach from logistics and assembly to maintenance [34]. While still in the prototype stage for some applications, industrial AR is gaining maturity, leading to an anticipated compound annual growth rate (CAGR) of the global industrial AR market of 75% between 2018 and 2025 leading to a market volume of more than $75 billion in 2025 [35].

The central part of an AR system, is the visualization hardware. A broad variety of devices to display the digital content are available. The main categories are head mounted devices (HMD), hand held devices (HHD), static screens, and projectors. All such systems have their advantages and drawbacks [36]. HMDs, however, bring together two highly relevant features for industry as they are hands-free and portable, which increases the positives effects of AR.

We conducted a qualitative survey amongst 85 industrial professionals [37], who have been involved with industrial AR pilot or implementation projects, shows that the industry involved by far most with AR is the automotive industry (see Fig. 4). 70% of the industrial AR pilot projects were conducted from 2015 onwards and 75% of AR trials led to permanently implementing the solution.

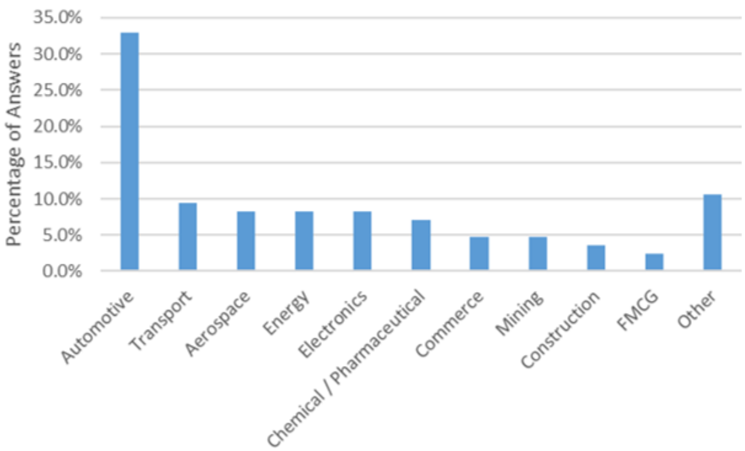

Fig. 3. Industries piloting or implementing industrial AR solutions (based on [37]).

The main focus of field experiments utilizing AR is to increase efficiency through decreasing the error rate and the task completion time by seamlessly integrating the information into the physical world. This leads to an economic benefit by reducing costs. Especially maintenance operations can profit from AR based instructions and AR tele-maintenance by reducing the time necessary for the task [38].

Despite its advantages, the implementation of AR into industrial operations introduces challenges. According to the survey participants, the main challenges are related to the operators using the technology. Especially ergonomic issues, like neck strain when using HMDs, or visual fatigue pose a challenge leading to the user acceptance to be rated as crucial for a successful implementation of industrial AR systems. Furthermore, industrial AR systems may require an adaption of the processes supported by AR so that the AR system can unfold its full potential.

Usually, industrial AR systems replace an already existing system for information transfer. Fig. 4. shows which pre-existing systems were replaced by the AR solution. Nearly 45% of the replaced systems were paper-based.

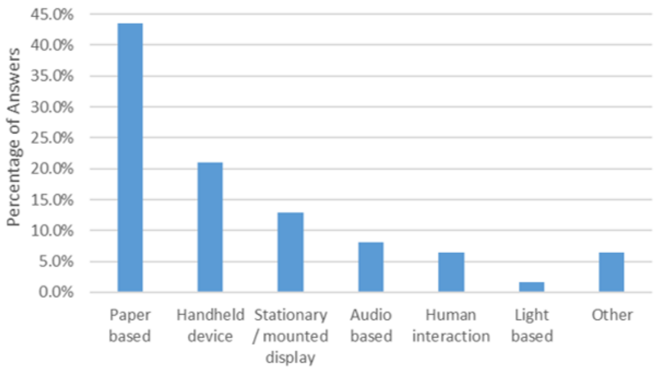

Fig. 4. Solutions replaced by an industrial AR system (based on [37]).

While industrial AR is widely recognized as a tool to increase efficiency through decreasing the error rate and the task completion time, industrial AR can also enable companies to utilize the intrinsic features of AR to future-proof TESS at an operational level, as the features of AR are aligned with a subset of future-proofing criteria presented in [1].

- *Flexibility and Reusability* - When undertaking planned changes of, for example altering the product architecture, direct and indirect changes along the assembly process and the supply chain propagate (see section 3). Currently, work orders, or assembly instructions are often paper-based. A change renders those paper-based information carriers obsolete. New instructions need to be designed, printed, and distributed. With an AR system, those changes can even be made in real-time. For maintenance applications, on-site content authoring through AR enables a swift and direct adaption of information when changes occur. This can be as simple as adapting for example checklists and placing digital information on certain places within the site to support maintenance personnel [39], or as complex as altering and rectifying incorrect maintenance tasks and information. These aspects of updating and reusing information and data can also improve the knowledge transfer as a pre-requisite for the future-proofing criteria. Giving technicians means to interact and alter the content enables gathering and transferring of the accumulated knowledge and experience of technicians throughout the organization.
- *Resilience* - Industrial AR facilitates a direct connection between the digital information without needing to go through physical steps. It is possible to display real-time information directly at the point of information consumption. Sudden and unexpected changes can cause the need to alter the information accessible to workers as soon as possible to recover. If, for example, a disruption in the production process occurs, which induces a re-routing of products to other assembly stations, workers can be informed directly that sequence changes occurred and that they need to alter their takt time.
- *System-stability* - Another aspect of future-proofing TESS through AR is a continuously monitored quality measures and assembly of the manufacturing process through the AR hardware. Once an assembly error is automatically detected, corrective measures can be displayed to maintain system-stability. While not commercially available, research is being conducted to make it a reality [40].

- *Operability / Information future-proofing* - A key pre-requisite to profit from industrial AR concerning resilience, adaptability, and reusability is information-future proofing [1]. While the high value products are often in use for a long time, the information around the product accumulated through the whole lifecycle beginning with the development, can be lost due to organizational or technological changes. Additionally, information like CAD drawings or assembly and maintenance instructions can be outdated because of the introduction of new variants or product updates. While coherent information and future-proofing of information is a pre-requisite to support the criteria to future-proof TESS (see Fig. 1), industrial AR can support updating the information directly from the field. Software, electronic components, and mechanical components get changed and updated over time at different frequencies [41]. Especially assets, for example machine tools, are subject to software and hardware changes along the lifecycle. Hence, maintenance technicians can be confronted with a system that substantially differs from the original state.

5. Conclusions

Future-proofing TESS is crucial in the current and future changing environments for their reliability across long life and reduced whole life costs. TESS future-proofing can be achieved by enabling disruption and change management capabilities. This paper has contributed by presenting (1) a concept of TESS future-proofing, (2) a framework of TESS future-proofing, and (3) case study examples of the framework application via: (i) CPM, and (ii) industrial AR, which can be utilized as enablers to future-proof TESS. It is important that the industry is aware that the CPM and AR type of enablers are available, so that the industry can proactively utilize such capabilities for future-proofing TESS. For academia, the future-proofing framework could act as guideline for other industry 4.0 technologies, e.g. additive manufacturing, cloud applications, and digital twins, on how to facilitate TESS future-proofing. This could also be an area of future research for further applications of the TESS future-proofing framework.

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